INTERFACE EVALUATION FOR OPEN SYSTEM ARCHITECTURES

THESIS

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Abstract

This research develops a deterministic interface evaluation framework (IEF) in support of the principles identified in the Modular Open Systems Approach (MOSA). Interface evaluation in weapon system development requires a Decision Analysis (DA) method capable of handling a continuously growing alternative set and functioning with limited availability of senior decision makers. Value Focused Thinking (VFT) is selected as the best method for addressing the parameters of the framework. Using input from the Medium Altitude Unmanned Aircraft System program office, the fundamental objectives of the interface evaluation framework are: Meet Schedule Expectations, Meet Acquisition Performance Expectations, and Minimize Acquisition Cost. An initial value threshold is established to guide open interface decisions, based on assessments of 15 historical decision scenarios. Open interface recommendations for the 15 scenarios are compared to previous program decisions, where the model supports past decisions for 5 of 15 scenarios. A sensitivity analysis is then conducted to examine the robustness of the framework to changing weights for cost, schedule, and performance, and the threshold for an open implementation decision. This evaluation framework provides a repeatable method for key interface evaluation that reflects the values of DoD acquisition leadership and the Open System Joint Task Force (OSJTF).

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Captain Joshua A. Burger

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I. Introduction

General Issue

The Open Systems Joint Task Force identifies modular system design and proper use of interface implementation methods as critical elements to cost effective system evolution (Open Systems Joint Task Force [OSJTF], 2004). A development team, within a system program office, must make decisions about the method of interface implementation that will be utilized across their system. While the OSJTF provides broad guidance on key interface identification and implementation method selection, it does not provide a specific tool or evaluation metrics (2004). Currently, these decisions are left to the judgment of subject matter experts or to contractor discretion which creates challenges for consistency and propriety. This document discusses the research conducted in the area of decision analysis for an evaluation framework that could be used to support Open System Architecture (OSA) decisions.

Background

United States Air Force weapons systems, specifically Medium Altitude Unmanned Aircraft Systems (UAS), are a disparate collection of subsystems and components integrated to achieve a military objective. This integration requires many decisions, during both the initial development and future modifications, about the interface implementation method (IIM) to be utilized between systems. Current IIM decision processes leverage expert judgment or rely on the judgment of the contractor.

DoD Directive 5000.01, a guiding document of the Defense Acquisition System, states, “a modular, open-systems approach shall be employed, where feasible” (Office of the Undersecretary of Defense for Acquisition Technology & Logistics, 2007, p. 9). Utilization of open interfaces is one of five major principles needed to implement a modular, open-systems approach (OSJTF, 2004). One could argue that, by definition, implementation of an open interface is always feasible; but is it worth it? Does the use of an open interface add value, and if so does the value it adds outweigh the costs, both monetary and temporal, of implementing the interface? A process and framework is needed to calculate the value of an open interface implementation.

UAS Background

The UAS is a collection of systems brought together for the purpose of conducting flight operations with an aircraft that does not have a pilot onboard (UAS Task Force Airspace Integration Integrated Product Team, 2011, p. A2). A weapon system must be adapted, where necessary, to changes in technology and adversary tactics. The term UAS originated from the Department of Defense and encompasses a wide variety of systems performing airborne missions without a human in the aircraft. The terms Remotely Piloted Aircraft (RPA), Remotely Piloted Vehicle (RPV), Remotely Operated Aircraft (ROA), Unmanned Aerial Vehicle (UAV), Unmanned Aircraft (UA), and drone are used synonymously with UAS (Greenemeier, 2011)(Federal Aviation Administration, 2013). Though the definitions of the terms are substantially different, for the purposes of this research, equal treatment of them is reasonable. UAS use as sensor and weapons platforms has increased in the years following the World Trade Center terrorist attacks of 2001. The attacks on the World Trade Center brought about a shift in combat operations from regular to irregular warfare (Greenemeier, 2011). This shift to irregular warfare drives a rapidly evolving threat matrix which changes the capabilities required to combat the threats. The proper method of interface implementation is critical to accommodating capability change with minimal impact to operations, sustainment, and development schedule.

Interface Implementation Methods

Understanding the theoretical levels of integration is critical to making IIM decisions. The Open Systems Joint Task Force (OSJTF) established the concept of a key interface, which has attributes that would benefit from an open standard interface. Open standard interfaces or industry standards are widely used and facilitate system flexibility or interoperability. The OSJTF identifies a non-key interface as having attributes that would not benefit from an open architecture which implies that a closed implementation would suffice. The OSJTF alludes to gradations between open standard and closed interfaces such as the "proprietary standard" or "de facto standard" (OSJTF, 2004). The gradations identified by the OSJTF imply the maturity of the interface standard.

Proper and consistent IIM decisions are critical to ensuring USAF technological dominance in the future. Improper interface implementation choice can lead to increased cost and schedule for system modifications, operations, maintenance and support and can ultimately lead to decreased mission performance. The study of IIM decisions and the creation of an interface evaluation framework (IEF), to evaluate the value of an open interface implementation, will enable clarity of thought for decision makers. Further, an IEF will provide decision makers with a method of determining the value of an open interface which will help to ensure proper and consistent IIM decisions are made throughout all levels of leadership. Resultantly, as highlighted by the OSJTF, judicious application of the open systems approach could decrease weapon system lifecycle cost and decrease the schedule associated with weapon system modification.

Problem Statement

Current decisions regarding IIMs are made based on intuition or are relinquished to the contractor and based on their preference and contractual strategy which may not be in the best interest of the government. This lack of a defined decision process often leads to hindsight determinations that key interfaces would have benefited from open standard methods. Failing to identify open standard methods as the proper IIM decision can result in increased modification cost and longer integration timelines throughout the lifetime of the weapon system. Conversely, open standard methods applied to non-key interfaces can cause resources to be consumed in pursuit of a modular open systems approach (MOSA) when not needed. Identifying open standard methods as the proper IIM when not needed results in underutilization of an open standard interface throughout the system lifecycle.

USAF weapons systems have many interfaces and thus require many IIM decisions to be made for successful fielding. This research will focus on an IEF to support UAS IIM decisions because of sponsor interest. The factors that make an open system interface valuable vary across the different perspectives of an integrated product team (IPT). The senior decision maker (SDM) is responsible for balancing all of the influences of the IPT when making decisions. Coalescing the IPT perspectives for a single IIM decision is a challenge for an SDM. This challenge is intensified when one considers the many interface decisions required on a UAS acquisition program. Currently no single framework provides guidance to SDMs for IIM decisions on UAS. A framework of this type could utilize deterministic evaluation measures derived from the values of the system program office to represent the value that decision makers place on an open interface. A clear understanding of the technical and programmatic factors, from many perspectives of an IPT, is needed. This collection of factors can be used to create a decision model from the perspective of a SDM in UAS acquisition. The model could be used by all levels of leadership to ensure that all factors are considered in IIM decisions and that decisions are consistent with the preferences of the SDM, ultimately leading to a balance of schedule, cost, and performance.

Research/Investigative Questions

The research question, below, indicates the overall focus of the research which will support defining a decision tool for IIMs that complements the broad guidance provided in the MOSA handbook.

Research Question:

- What is an evaluation framework for assessing the value of an open interface implementation?

The research question will be addressed through detailed investigation of the areas highlighted by the investigative questions below.

Investigative Questions:

- What attributes are considered when determining the value of an open interface implementation?

- What is the structure of an open interface evaluation framework; including the value hierarchy, single attribute value functions, weight factors, and multiattribute value function?

- What are the single-attribute value functions associated with the IIM value hierarchy?

- What value scores align with an open IIM selection?

Assumptions and Limitations

The research described in this document is constrained by several key assumptions and research limitations. The first assumption is that a planning horizon will be utilized to scope the framework development. The planning horizon is a timeframe that must be considered when formulating all elements of a decision model. The planning horizon can influence the decision factor elicitation, value measure bounds, value function development, weight factor determination, and alternative scoring. In many cases a temporal element is associated with decision factors. It is important to constrain the planning horizon to ensure that elicited factors and value measures account for the same length of time. As an example, if one were evaluating housing options and were considering both renting and purchasing a home factors such as neighborhood, school district, and number of bedrooms may be valued differently if the planning horizon were one year as opposed to ten years. The second assumption is that input from a single UAS program will be representative of other UAS programs. The research will leverage a set of IPT-level contributors that provide a variety of perspectives on open interface decisions. However, the IPT members and the SDM will come from the same UAS program. This is a deliberate decision to ensure breadth of input across IPT functional areas within the time constraints of the research. The third assumption is that of preferential independence between the fundamental objectives of the value hierarchy. The concept and implications of preferential independence are discussed in detail in chapter 2. The final assumption is that an interface scenario under consideration will meet the technical performance requirements for the connected systems. The implication of this assumption is that interface technical performance is not considered in the evaluation framework. A limitation of the research methodology is the assumption of certainty of all decision factors. It is assumed that the individual using the IEF will have a certain answer to all decision factors for the period of the planning horizon. This is an idealistic assumption that will limit the applicability of the model. The concept of including uncertainty in the framework will be discussed as part of chapter 2, but was not executed in this research effort.

Methodology Overview

The research discussed in this document will be conducted in the following four phases utilizing qualitative data collected to support the Value Focused Thinking (VFT) decision analysis method: hierarchy development, value function development, factor weighting, and analysis. As an alternative to VFT, the Analytic Hierarchy Process (AHP), was considered as a viable methodology for IEF development. However, AHP is best applied to one time decisions with direct decision maker interaction (Belton, 1986). The ultimate goal of this research is to produce a model that can be leveraged at multiple organizational levels to support repetitive IIM decisions consistent with SDM preferences without direct engagement by the SDM. VFT was chosen over AHP because, while both methods could be utilized, the focus of this thesis is on repetitive decisions without direct SDM involvement.

Each phase of the research has specific qualitative data used by the analysis method. The hierarchy development phase of the research will employ IIM value factor data from academic and doctrinal publications (the gold standard) and elicitation with six UAS IPT members (the silver standard) from various functional areas including, program management, engineering, logistics, finance, contracting, and operations(Parnell, Bresnick, Tani, & Johnson, 2013). These factors will be defined, aggregated, and organized into an affinity diagram followed by a value hierarchy. After the value hierarchy is complete, value preference data elicited from a UAS SDM will be used to form single attribute value functions (SAVF) for each of the lowest level hierarchical elements. Upon completion of the SAVF, development weight factors elicited from the UAS SDM using swing weighting techniques will be utilized to establish a Multiattribute Value Function (MAVF). To verify that framework is consistent with the SDM's values, consistency checks will be implemented in each stage of the development. The quality of the model will be validated with a subjective assessment of the hierarchy against the areas of completeness, non-redundancy, decomposability, operability, and conciseness (Kirkwood, 1996). Finally, the framework will be used to analyze interface implementation scenarios from the MQ-1/MQ-9 program to make comparisons between the theoretical model and historical precedence.

Document Overview

The remainder of the document is subdivided into four chapters. Chapter 2 provides a review of research conducted in the areas of MOSA, AHP, VFT, preferential independence, and uncertainty in multiattribute value models. Chapter 3 provides a detailed account of the methodology of the research, and Chapter 4 provides results and discussion from the research conducted in the previous chapter. Finally, Chapter 5 provides recommendations based on the results obtained during this study and future research opportunities in this area.

II. Literature Review

Modern weapon systems are complicated collections of interacting subsystems and components brought together to deliver unique capabilities (Office of the Deputy Under Secretary of Defense for Acquisition and Technology, Systems and Software Engineering, 2008). To develop these weapon systems, the subsystems and components must be connected in a way that optimizes total system performance. To achieve optimal performance it is critical that development teams consider all relevant factors to total system performance when making decisions about the IIM employed.

The research contained in this document is focused on developing a framework to aid effective and consistent open interface decision-making. This chapter discusses relevant and current literature addressing two critical elements supporting this research effort: open systems and decision analysis. First, a detailed exploration of the MOSA is conducted. Next, two primary decision analysis methods, the AHP and VFT, are discussed. Then a detailed explanation of the execution of the VFT decision model development process is provided. Finally, Chapter 2 will conclude with an examination of techniques for the inclusion of uncertainty in multiattribute decision models.

Modular Open Systems Approach

The OSJTF defines MOSA as “both a business and technical strategy for developing a new system or modernizing an existing one” (2004, p. 2). This section describes the benefits of an open systems approach in the systems engineering process. Then the overarching defense department policies associated with MOSA are outlined.

Finally, a summary of the guidance provided by the OSJTF on MOSA implementation is provided.

Open Systems Approach in the Systems Engineering Process

"Today, legacy weapon systems continue to be developed with their own, often unique and frequently closed, infrastructures, making upgrading or modifying them over their expected lifetimes (20 to 40 years) both problematic and expensive" (Hanratty, Lightsey, & Larson, 2002, p. 1). Additionally, Hanratty, et al. (2002) highlight that the problem of expensive weapon system modification is exacerbated by shrinking budgets and technology evolution driven by commercial demands. The authors assert that, in addition to cost savings, the open systems approach enables weapon systems to keep pace with technology change and provides a tactical advantage from faster integration of new technology (Hanratty et al., 2002). The benefits highlighted by the OSJTF in Figure 1 reinforce the assertions made by Hanratty, et al. The open systems approach is not intended to replace the systems engineering process but, instead, should be incorporated into it to have the maximum positive impact. Further, the use of open architectures should not be applied to all elements of a system. Openness should be employed where its benefits provide a cost, schedule, and/or tactical advantage (OSJTF, 2004).

OSA/MOSA Policy

In a 2004 memorandum from the Office of the Under Secretary of Defense, Director for Defense Systems stated that "A Modular Open Systems Approach… is an integral part of the toolset that will help DoD achieve its goal of providing the joint combat capabilities required for the 21st century" (Lamartin, 2004, p. 1). In that same document Larmartin named the OSJTF as the lead for MOSA.

The MOSA was cemented as part of DoD acquisition policy. The approach was part of systems engineering direction in DoD Directive 5000.01, a document that "provides management principles and mandatory policies and procedures for managing all acquisition programs" (Office of the Undersecretary of Defense for Acquisition Technology & Logistics, 2007, p. 4). MOSA was further reinforced, in DoD Instruction 5000.02, with direction for program managers to employ the approach "to design for affordable change, enable evolutionary acquisition, and rapidly field affordable systems that are interoperable in the joint battle space" (Office of the Undersecretary of Defense for Acquisition Technology & Logistics, 2008, p. 79). The *Program Manager's Guide: A Modular Open Systems Approach (MOSA) to Acquisition* was created by the OSJTF to provide acquisition professionals guidance for implementing MOSA (OSJTF, 2004).

In 2013, DoDI 5000.02 was revised and the term MOSA was removed in favor of the term OSA. The Interim DoD 5000.02 continued to instruct that "program managers will use open systems architecture design principles to support an open business model" (Office of the Undersecretary of Defense for Acquisition Technology & Logistics, 2013, p. 85). The interim guidance referenced a new guidebook, the *DoD Open Systems Architecture Contract Guidebook for Program Managers*, which focuses on the business aspects of implementing an OSA. This new guide provides a more detailed account of contracting methods for OSA, but references the 2004 OSJTF document for the technical aspects and principles of implementing a MOSA (Department of Defense Open Systems Architecture Data Rights Team, 2013).

MOSA Guidance:

The overarching goal of the MOSA is to enable affordable change through modular system design and employment of open standards. The OSJTF indicates that this is achieved when MOSA technical strategies are not only employed, but incorporated into the business strategies of an organization (OSJTF, 2004). Figure 1 highlights the vision, principles and benefits of the approach.

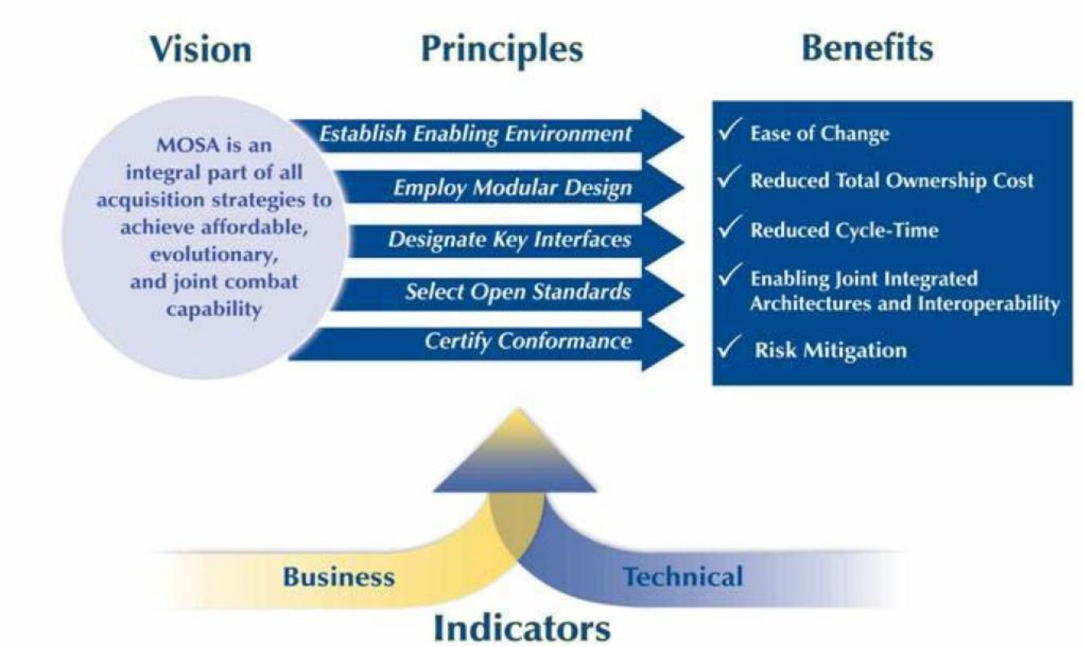


Figure 1: Modular Open Systems Approach (OSJTF, 2004, p. 3)

"<u>Principle 1: Establish an Enabling Environment</u>" (OSJTF, 2004, p. 11)

This principle indicates that the program manager must build an integrated product development and support atmosphere that is capable of supporting modular design. Supporting modular design can have implications for development, contracting, test, and system support. Additionally, modularity requires special consideration in a program's strategic and management planning (OSJTF, 2004).

"Principle 2: Employ Modular Design" (OSJTF, 2004, p. 13)

This principle aims at dividing the system into functional elements that can be "developed, maintained, and modified or upgraded" (OSJTF, 2004, p. 5) independently. A modular design requires decomposition of the high level system into lower level systems and identification of interfaces between interacting systems.

"Principle 3: Designate Key Interfaces" (OSJTF, 2004, p. 14)

The OSJTF defines a key interface as an "interface for which the preferred implementation uses an open standard to design the system for affordable change, ease of integration, interoperability, commonality, reuse or other essential considerations such as criticality of function" (OSJTF, 2004, p. 14). The guide recommends evaluating each interface based on the above qualitative characteristics, but does not provide any specific metrics for key interface determination. The MOSA guide recommends the use of a work breakdown structure or a technical reference model, example in Figure 2, to help identification of potential interfaces. Figure 2 represents an example aircraft divided into many high level modules. Each module can be further subdivided until specific interfaces can be identified. The organization managing the aircraft development must make a business decision as to what level of subdivision and subsequently interface control is desired (OSJTF, 2004).

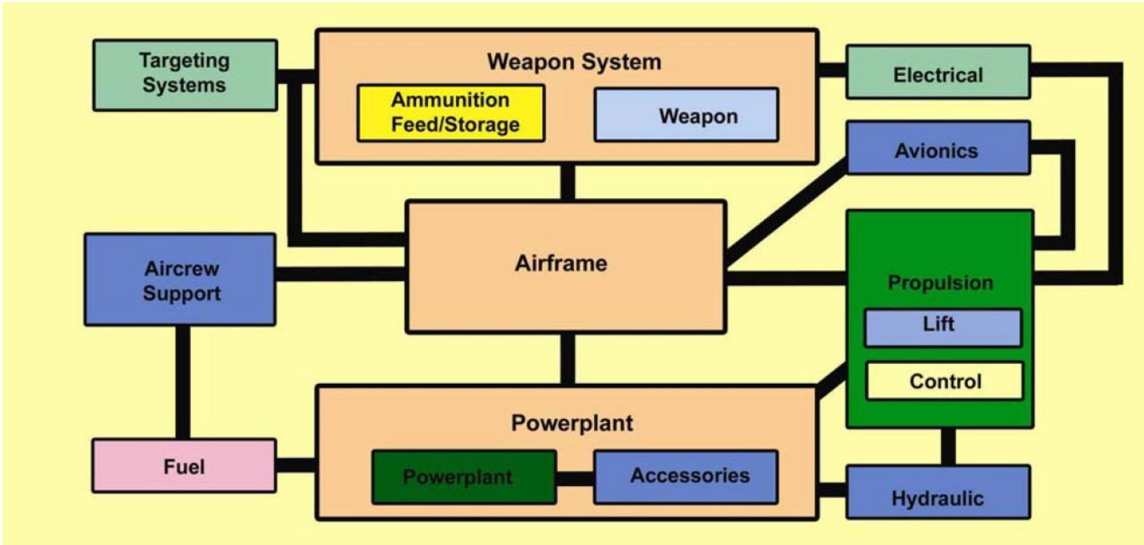


Figure 2: Example Technical Reference Model (OSJTF, 2004, p. 15)

"Principle 4: Use Open Standards" (OSJTF, 2004, p. 16)

The OSJTF defines an interface standard as "a standard that specifies the physical, functional, and operational relationships between various elements (hardware and software), to permit interchangeability, interconnection, compatibility and/or communications" (2004, p. A2). Additionally open standards are defined as "standards that are widely used, consensus based, published and maintained by recognized industry standards organizations" (OSJTF, 2004, p. A3). The guide indicates that once key interfaces are identified the feasibility and appropriateness of implementing an open standard should be considered. Table 1 shows a list of factors to consider when making this determination. The table does not indicate specific metrics for the factors nor an indication of each factors relative importance to the decision.

Table 1: Open Standard Implementation Decision Factors

Factor	Description
1	“Overall acquisition strategy (e.g., the likelihood that the technologies/engineering for full capability still need to be developed and whether or not the longer-term requirements are stable or addressed as evolving increments.)” (OSJTF, 2004, p. 16)
2	“Need to take advantage of competition throughout the life cycle” (OSJTF, 2004, p. 16)
3	“Support strategy (e.g., the extent of market acceptance and availability of products that comply with a selected standard)” (OSJTF, 2004, p. 16)
4	“Availability, maturity, verification, and accreditation of standards for an interface” (OSJTF, 2004, p. 16)
5	“Need for minimizing integration risks over the life of the system” (OSJTF, 2004, p. 16)
6	“The intensity and magnitude of risks associated with a proprietary interface standard” (OSJTF, 2004, p. 16)
7	“The degree of dependency on rapidly evolving technology and the technology readiness level for the components or items at both ends of an interface” (OSJTF, 2004, p. 16)
8	“Need for flexibility, modularity, and interface control” (OSJTF, 2004, p. 16)

“Principle 5: Certify Conformance” (OSJTF, 2004, p. 17)

This principle is focused on the validation and verification of open standards implemented on a weapon system. The OSJTF indicates that when an open architecture is employed system performance testing is no longer sufficient. System testing and certification must incorporate testing of open standard conformance where applicable (OSJTF, 2004).

Decision Analysis

Establishing whether an open interface implementation is "worth it" is a complex decision. Assuming either an open or closed interface implementation would perform equally well against technical requirements, many remaining factors must be considered, such as the cost, schedule urgency, and amount of change. These factors and many others impact whether implementing open is "worth it" or not. In an explanation of why decision analysis is valuable Belton (1986) states, "we are looking for an approach which will aid the decision maker in analysis and synthesis of detailed information in a way in which is consistent with her value judgments about the relative importance of her objectives" (p. 2). Before committing to an "irrevocable allocation of resources," decision makers should ensure they have an adequate understanding of the decision under consideration (Howard & Abbas, 2010, p. 12). Decision analysis is a field focused on helping a decision maker obtain clarity of thought and understanding for decisions that are too complex to be addressed with intuition or simple logic. The fundamental "goal is to structure and simplify the task of making hard decisions as well and as easily as the nature of the decision permits" (Von Winterfeldt & Edwards, 1986, p. 2). The two primary contributors that make decisions complex are uncertainty and multiple conflicting objectives. Uncertainty in decision making with a single objective is a well understood concept in which the decision maker is faced with multiple choices with unknown future states. The choice of future states will result in a gain or loss of a single utility measure such as money or time. The best decision is associated with the highest expected utility. Multiple conflicting objectives in decision making is the concept of competing values, objectives and goals (Keeney & Raiffa, 1993) (Von Winterfeldt &

Edwards, 1986). This research focuses on the evaluation of interface scenarios in the acquisition environment where new alternatives are analyzed with consideration of a common set of value measures or objectives. Belton (1986) indicates that AHP and VFT, a version of Multi-Attribute Value (MAV) theory popularized by Keeney, are the best approaches for decisions of this nature after considering many other options such as Paretian cost benefit analysis, Social cost benefit analysis and Multi-Objective Decision Modeling techniques applied to continuous decision problems. Bard strengthens Belton's assertion by stating that AHP and VFT offer "an integrated framework in which the decision maker can conduct tradeoffs among incommensurate criteria without having to rely on a single measure of performance" (1992, p. 111).

Analytic Hierarchy Process

The AHP is one of two widely used approaches in the field of discrete multiple criteria decision making. The AHP begins with the creation of a value hierarchy which maps the objectives of the decision space. Little specific guidance is provided on the construction of the hierarchy. The AHP is focused on the process of establishing scores and weights for a value function (Belton, 1986). The process employs a semantic scale, measuring connotative meaning, which is aligned with a 1-9 numeric scale, shown in Table 2, for use in the development of a pairwise comparison matrix (Saaty, 1980). Belton's (1986) comparison of AHP and simple multiattribute value function indicates that AHP is best used directly by a decision maker for a single decision scenario because of the use of the semantic scale. The hierarchy developed for a single decision could be used for repetitive decisions, but because the interpretation of each level of the semantic scale is unique to the decision maker that developed the hierarchy, his or her involvement would still be required. The AHP employs a pairwise comparison technique for alternative scoring and weight factor determination (Belton, 1986). The technique for

Table 2: Analytic Hierarchy Process Semantic Scale (Belton, 1986)(Saaty, 1980)

1	Equally Preferred	Intermediate values may be used as appropriate.
3	Weak Preference	
5	Strong Preference	
7	Demonstrable Preference	
9	Absolute Preference	

scoring alternatives involves the decision maker answering n(n-1)/2 questions about strength of preference, where n = the number of factors being compared to fill the comparison matrix (Bard, 1992). A criticism of pairwise comparison with a semantic scale is that it assumes a ratio scale for scoring. For example, if the decision maker strongly prefers alternative A to alternative B, alternative A would be scored a 5; if the opposite were true, it would be scored a 1/5. Similar to alternative scoring, pairwise comparison of decision criteria is used to determine weight factors. The consistent application of the same process, pairwise comparison, is beneficial to an untrained decision maker. The weight factors in AHP are criticized because their meaning is not readily understood. The weight factors and alternative scores are used to generate a prioritized list of alternatives. To trust the results of the determinations, the decision maker must use a consistency index to ensure consistency of judgment across the weights and alternatives. If consistency has not been achieved, the decision makers must examine the assessment inconsistencies and reassess their preferences. A final limitation of the AHP is that it is not appropriate for problems that involve uncertainty (Belton, 1986).

Value Focused Thinking

VFT is the second of two widely used approaches in the field of discrete multiple criteria decision making that are discussed in this chapter. A fundamental tenant of VFT is the focus on values prior to the identification of alternatives. This tenet allows the decision makers to maintain an open mind about the alternatives which could be effective solutions to problems. Additionally, this allows the SDM to develop a decision model without having a complete set of alternatives. The mathematical underpinning of VFT is multiattribute utility theory which leverages the assumption of mutual preferential independence to employ an additive value function in deterministic models (Keeney, 1992). The mutual preferential independence assumption indicates that the value score of a particular attribute has no effect on the value score of any other attribute (Von Winterfeldt & Edwards, 1986). In many instances preferential independence does not hold for all factors. When interaction exists between factors a value function with partial additivity can be employed (Keeney & Raiffa, 1993). This concept is explored in more detail in the preferential independence section. The use of component value functions allows repeated use of the model for similar decisions and allows individuals other than the SDM to utilize the model (Belton, 1986). A detailed account of the ten step VFT model development process is provided following further examination of preferential independence. Some common VFT terms are provided in Table 3, to aid the reader in comprehension of the remaining VFT related sections.

Preferential Independence

Mutual Preferential Independence (MPI) is a driving assumption behind the additive value function. This section explains the concept of preferential independence, implications of scaling constants, MPI verification, and the use of value functions with partial additivity.

Preferential Independence assumes that a SDMs preferences over a single attribute are unaffected by the levels of the other attributes (Von Winterfeldt & Edwards, 1986). Given a value space that contains four attributes (x_1, x_2, x_3, x_4) and that x_1 is the attribute under consideration, x_1's complementary set is (x_2, x_3, x_4).

The additive functional form is a specialization of the multilinear functional form in which no interaction terms exist. MPI is a condition, where preferential independence exists between all combinations of attributes, which allows for exclusion of the interaction terms. The multilinear functional form for two factors is shown in equation (1). If the interaction terms, highlighted by the red square are removed, equation (2), the additive functional form is left. The inclusion of interaction terms adds great complexity to the mathematical representation of the SDMs preferences and also adds significant additional time and work to the data collection process (Keeney & Raiffa, 1993).

Table 3: VFT Terminology

Strategic Objective	"…provides common guidance to all decisions" (Keeney, 1992, p. 41). Serves to guide the fundamental objectives.
Fundamental Objective	"…an essential reason for interest in the decision situation" (Keeney, 1992, p. 34).
Value	What is important to the decision maker (Clemen, 1996, p. 19). "The values are the decomposition of the fundamental objective. They are the building blocks of the value hierarchy" (Jurk, 2002, p. 27).
Value Structure	"…the entire set of evaluation considerations, objectives, and evaluation measures for a particular decision analysis" (Kirkwood, 1996, p. 12).
Value Hierarchy	"A value structure with a hierarchical structure" (Kirkwood, 1996, p. 12).
Global Weight	The scaling constant applied to a lowest level value that captures the individual value's relative contribution to the value score of an alternative. All global weight sum to one (Keeney & Raiffa, 1993, pp. 118-123)
Value Measure	Measurement of the "degree of attainment" of a value using a scale relevant to the particular value (Kirkwood, 1996, p. 12) .
Score	The "specific numerical rating for a particular alternative with respect to a specified evaluation measure" (Kirkwood, 1996, p. 12).
Alternative	The subject of evaluation that performs to a specific level on all elements of the value structure (Keeney & Raiffa, 1993, p. 66).
Component Value Function (CVF)	The function converts the value score/s based on the value measure into a common scale measured in value (Keeney & Raiffa, 1993, p. 119).
Value Function	A function that captures the relative importance for all CVFs (Keeney & Raiffa, 1993, p. 80).

(1)

$$
{}^{*}v(x_1, x_2, x_3) = k_1 \cdot v_1(x_1) + k_2 \cdot v_2(x_2) + k_3 \cdot v_3(x_3) \\
\boxed{\begin{aligned} &+ k_{12} \cdot v_1(x_1) \cdot v_2(x_2) + k_{13} \cdot v_1(x_1) \cdot v_3(x_3) \\ &+ k_{23} \cdot v_2(x_2) \cdot v_3(x_3) + \mathrm{k}_{123} \cdot v_1(x_1) \cdot v_2(x_2) \cdot v_3(x_3) \end{aligned}}
$$

Where

$v_i(x_i) =$ CVF

$\mathrm{k}_i =$ Scaling constant

$\mathrm{k}_{ij} =$ Scaling constant for pairwise interaction

$\mathrm{k}_{ijk} =$ Scaling constant for triplet interaction

*Note: Equation (1) is a modification of the multilinear utility function captured in Chapter 6 of the Keeney and Raiffa (1993) text. This modification was executed to show the use of SAVFs rather than Uni-Dimensional Utility Functions.

(2)

$$
v(x_1, x_2, x_3) = v_1(x_1) + v_2(x_2) + v_3(x_3)
$$

The pairwise scaling constants employed in the multilinear functional form indicate the interaction relationship between the attributes. If k_{ij} equals zero then it indicates that interaction between the attributes has no impact on the value of an alternative. A k_{ij} greater than zero indicates a complementary relationship between the attributes. The complementary relationship is one in which more value is obtained when high scores are achieved for the interacting attributes. A k_{ij} less than zero indicates a substitution relationship between the attributes. This relationship is one where a high value score can be obtained with a high level of either X_i or X_j. The additional value gained from a high level of both X_i and X_j is less significant (Keeney & Raiffa, 1993).

Verification of MPI requires examining n-1 pairs of attributes while systematically varying the complementary set of attributes, where n is the total number of attributes (Kirkwood, 1996)(Keeney & Raiffa, 1993). "In practice, it would not be reasonable to check directly for all possible preferential independence conditions" (Keeney & Raiffa, 1993). Ting indicated that identifying natural attribute groups would facilitate MPI verification (as cited in Keeney & Raiffa, 1993, p. 115). The strategic objective of a hierarchy may be broken into several fundamental objectives, each of which is most likely broken down further. If MPI can be determined between the groups, then an additive value function can be employed between the fundamental objective groups. This technique can be employed from the top down in a value hierarchy examining the sub-objectives of each fundamental objective. This systematic examination expedites the determination of MPI (Keeney & Raiffa, 1993).

In the event that MPI does not exist, value functions with partial additivity can be employed (Keeney & Raiffa, 1993). A way to illustrate this is with an example. Consider a simple value hierarchy with the strategic objective divided into two fundamental objectives (X, Y). Fundamental objective X has sub-objectives X_1 and X_2. Fundamental objective Y has sub-objectives Y_1 and Y_2. This example demonstrates the the simplification achived with the MPI assumption. The existence the partial preferential independence condition enables the development of a greatly simplified value function.

Without MPI

$$
\begin{aligned}
V(x_1, x_2, y_1, y_2) = {} & v(x_1) + v(x_2) + v(y_1) + v(y_2) + \left(k_{x1x2} \cdot v(x_1) \cdot v(x_2)\right) + \left(k_{x1y1} \cdot v(x_1) \cdot v(y_1)\right) + \left(k_{x1y2} \cdot v(x_1) \cdot v(y_2)\right) \\
& + \left(k_{x2y1} \cdot v(x_2) \cdot v(y_1)\right) + \left(k_{x2y2} \cdot v(x_2) \cdot v(y_2)\right) + \left(k_{y1y2} \cdot v(y_1) \cdot v(y_2)\right) + \left(k_{x1x2y1} \cdot v(x_1) \cdot v(x_2) \cdot v(y_1)\right) \\
& + \left(k_{x1x2y2} \cdot v(x_1) \cdot v(x_2) \cdot v(y_2)\right) + \left(k_{x1y1y2} \cdot v(x_1) \cdot v(y_1) \cdot v(y_2)\right) + \left(k_{x2y1y2} \cdot v(x_2) \cdot v(y_1) \cdot v(y_2)\right) \\
& + \left(k_{x1x2y1y2} \cdot v(x_1) \cdot v(x_2) \cdot v(y_1) \cdot v(y_2)\right)
\end{aligned}
$$

With MPI

$$V(x_1, x_2, y_1, y_2) = v(x_1) + v(x_2) + v(y_1) + v(y_2)$$

With preferential independence between fundamental objectives

$$V(x_1, x_2, y_1, y_2) = v(x_1, x_2) + v(y_1, y_2)$$

$$V(x_1, x_2, y_1, y_2) = \left(k_{x1} \cdot v(x_1) + k_{x2} \cdot v(x_2) + k_x \cdot v(x_1) \cdot v(x_2)\right) + \left(k_{y1} \cdot v(y_1) + k_{y2} \cdot v(y_2) + k_y \cdot v(y_1) \cdot v(y_2)\right)$$

VFT Model Development Process

VFT model development follows a 10 step model development process. A flow chart shown in Figure 3, modified from that created by Shoviak (2001), depicts the sequenced activities of VFT model development (p. 63). This process provides the decision maker or facilitator with a guide to navigate VFT utilization. Each step of the process is explained in detail in the following sections.

Step 1: Problem Identification

The problem identification step is intended to ensure complete understanding of the decision under consideration. Establishing the decision frame facilitates this understanding and allows the decision maker to determine the factors that are important

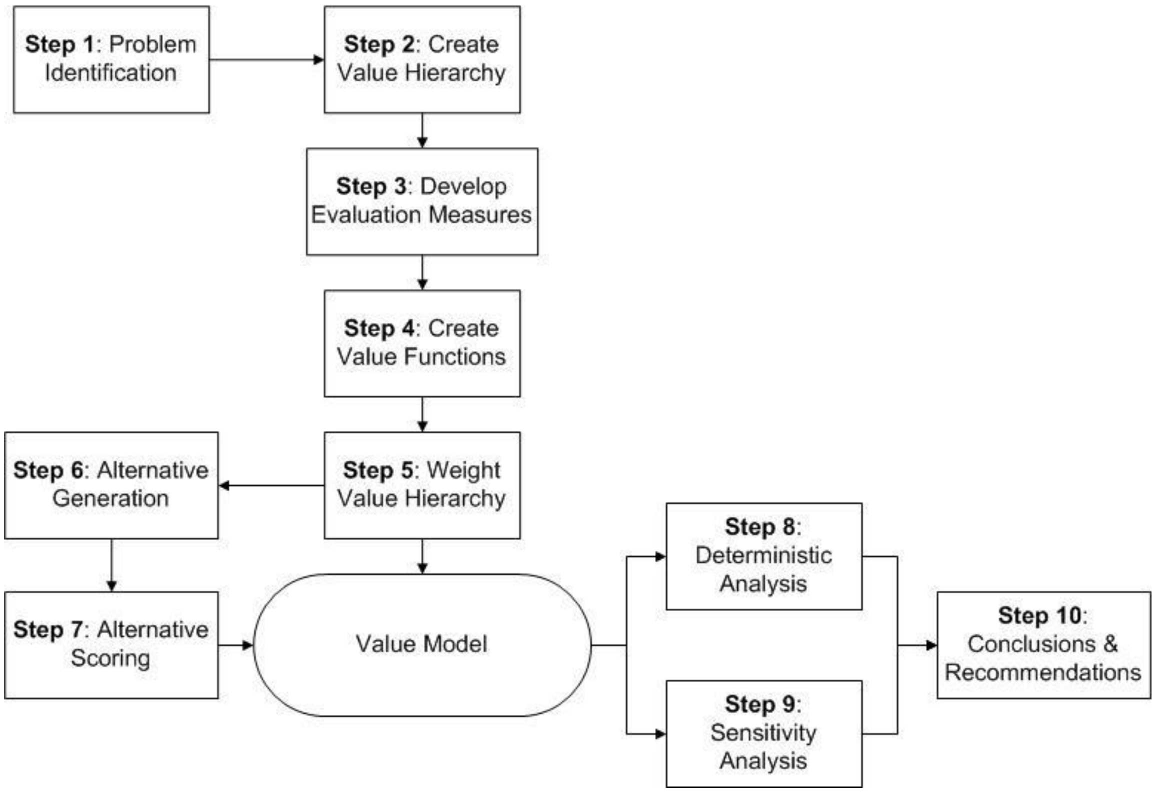


Figure 3: Decision Support Model Development Framework (Shoviak, 2001)

to evaluating a decision. The decision frame is comprised of the decision context and the fundamental objectives. These elements provide the guidance upon which the decision model will be based and establish decision boundaries such as time horizon and perspective (Keeney, 1992).

Step 2: Create Value Hierarchy

The value hierarchy is a structured representation of salient factors to a decision maker with respect to a particular decision. The hierarchy is constructed with a strategic objective, overall goal, at the top level and then sub-divided in more detailed lower-level objectives until all relevant factors are depicted (Keeney & Raiffa, 1993). The goal of a finished hierarchy is to be complete, non-redundant, decomposable, operable, and concise. To be complete, the hierarchy must encompass all germane factors to a decision situation. Non-redundancy focuses to ensure that the same or similar factors are not used twice in the same tier of the hierarchy. A hierarchy is decomposable if its factors are independent, meaning that one factor does not influence the value judgment of another factor. The term operable indicates that the factors of the hierarchy are understood by the user. Finally, the concept of conciseness is to keep the hierarchy as small as possible to facilitate SDM understanding (Kirkwood, 1996). In addition to the five attributes of a good hierarchy listed above, a sixth attribute, input quality contributes to the credibility of an evaluation framework. Three approaches to obtaining the information to build the value hierarchy have been described. The *silver standard* approach, regarded as the least desirable of the three, requires elicitation of decision factors from decision maker representatives. This approach is typically utilized if the decision maker is time constrained or unavailable to provide direct input. The *gold standard* approach involves obtaining the information from doctrinal documentation such as vision statements, operating instructions, or strategic plans. Finally, in the *platinum standard* approach hierarchy inputs are elicited directly from the decision maker and can be regarded as the most accurate representation of their preference structure (Parnell et al., 2013).

Step 3: Develop Evaluation Measures

The final step in the hierarchy development is to establish evaluation measures for the lowest level objectives. The goal of this step is to establish a quantitative measure, also referred to as an attribute, which can reflect the value associated with a particular objective. This measure can then be mathematically associated with a value score through the use of a CVF which is created in Step 4. The value measures are categorized into the four types shown in Table 4, in order of preference (Keeney, 1992). Regardless of the value measure type used, the scale should be clear and meaningful to the SDM. The end points of the scale should be chosen such that they are likely to be inclusive of any future alternative (Von Winterfeldt & Edwards, 1986). The end points are used in the construction of CVFs. If a future alternative was presented that did not fall within

Table 4: Types of Value Measures (Parnell et al., 2013)

Preference	Type	Measurement Method	Description
1	Natural	Direct	The measure is commonly interpreted and directly measures the subject objective.
2	Constructed	Direct	The measure was either constructed specifically for the hierarchy or must be explained and directly measures the objective.
3	Natural	Proxy	The measure is commonly interpreted and does not directly measure the objective.
4	Constructed	Proxy	The measure was either constructed specifically for the hierarchy or must be explained and does not directly measure the objective.

the bounds of the scale it could not be compared to existing alternatives without reworking multiattribute value function and re-assessing all previously assessed alternatives.

Step 4: Create Value Functions

After evaluation measures and appropriate scales have been determined, the decision maker, or facilitator, must develop CVFs for each measure. This section examines qualitative characteristics/implications and techniques used in the establishment of CVFs.

Value measures have two attributes that should be considered before creating the CVFs. First, a value measure can be either continuous or discrete. Second, a value measure can be monotonically increasing, monotonically decreasing, or non-monotonic. The monotonically increasing (decreasing) case has increased (decreased) value as the measure increases. In the non-monotonic case, value rises then falls as the measure increases. This phenomenon typically reveals a merger of conflicting values and can be resolved through further examination of the value hierarchy. The purpose of the CVF is to convert the scale for each value into a common value scale. When preferential independence exists between values, the CVF is referred to as an SAVF.

There are four primary shapes of SAVFs for continuous value measures: Linear, Concave, Convex, S-Curve. A decision maker's value preferences may be different for each objective (Parnell et al., 2013). The SAVFs are constructed in accordance with the inputs of the decision maker and allow for the model to precisely match the preference structure (Keeney, 1992)(Keeney & Raiffa, 1993). The implications of the four categories, illustrated in Figure 4, are explained based on an assumption of a monotonically increasing value measure. The linear function represents a constant valuation, where each unit of the value measure holds the same amount of value for the SDM. This is often utilized for monetary attributes. The concave (convex) function has decreasing (increasing) marginal value, where each unit of the value measure holds less (more) value as it approaches the maximum. Concave and convex functions are typically represented with an exponential curve fitting operation. The S-Curve function captures both a convex and concave region. This is typically representative of a value measure with an optimal point or goal. In the case of a monotonically decreasing measure the implications of each function are simply reversed. When the value measure has a small

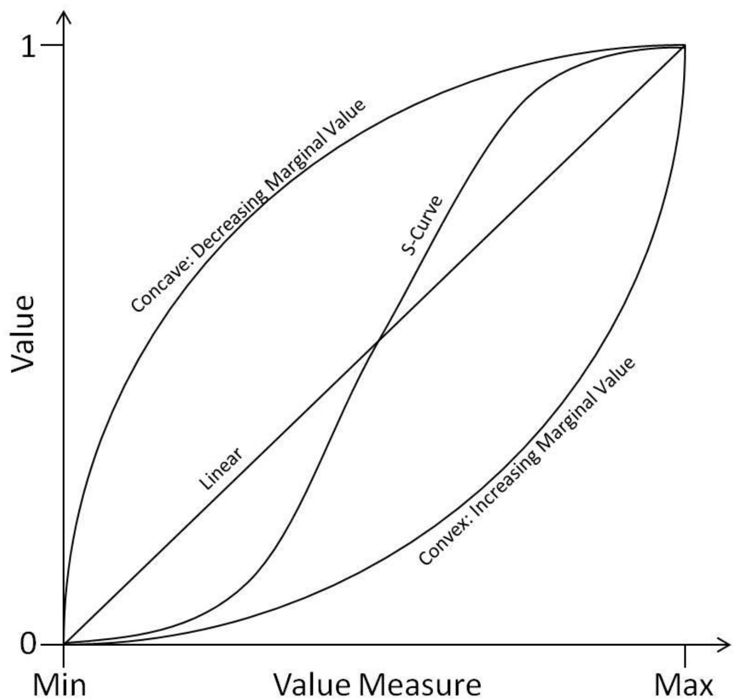


Figure 4: Example SAVFs (Parnell et al., 2013, p. 196)

number of discrete levels a categorical value function, illustrated in Figure 5, can be employed (Parnell et al., 2013). The SAVFs described have all hinged on the assumption of preferential independence, where the value of a single attribute is not dependent on the value of any other single attribute in the value structure. When this assumption does not hold the facilitator must account for interaction between the attributes. This can be captured utilizing the multilinear functional form shown in equation (3) (Keeney & Raiffa, 1993).

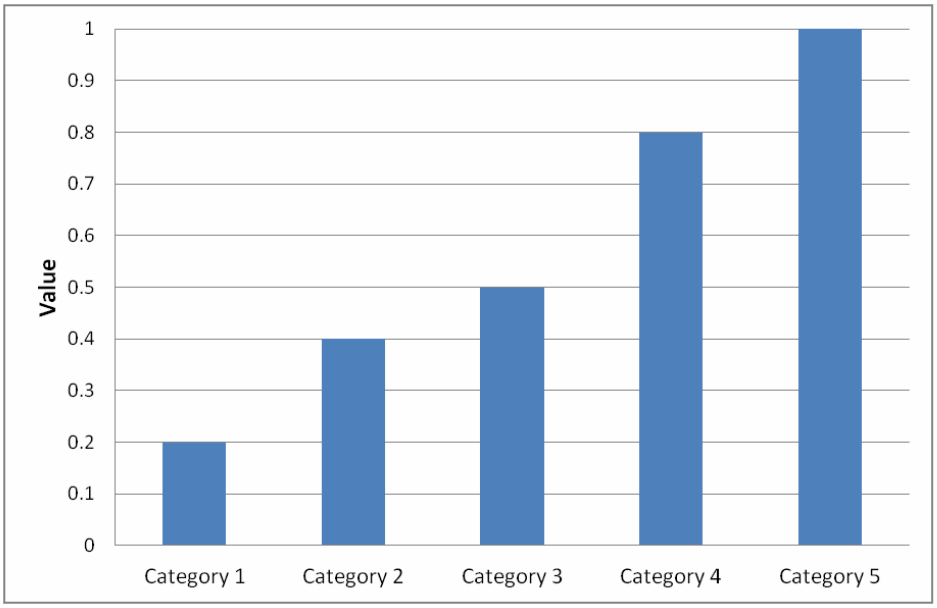


Figure 5: Categorical Single Attribute Value Function

(3)

$$v\ (X) = \sum_{i=1}^{n} s_i \cdot v_i(x_i) + \sum_{i=1}^{n} \sum_{j>1} s_{ij} \cdot v_i(x_i) \cdot v_j(x_j)$$

Where

$X \equiv$ The interacting attributes

$s_i =$ Scaling Constant for attribute i

$v_i(x_i) =$ SAVF for attribute i

$s_{ij} =$ Scaling Constant for the Interaction between attribute i and j

CVFs are constructed utilizing either silver or platinum inputs, as described above, obtained through one of three elicitation techniques; direct rating, difference standard sequence, and bisection. The fundamental goal of the elicitation process is to attain enough information from the SDM to characterize the value space and check for consistency (Von Winterfeldt & Edwards, 1986).

Direct rating is a numerical estimation technique employed when there are a small number of discrete levels in the value measure or when there is small set alternatives under consideration and the SDM can make firm judgment about preferences between levels. The SDM is first asked to identify the most preferred and least preferred level. The most preferred level is assigned a value score of 1 and the least preferred level is assigned a value score of 0. The SDM is then asked to score the intermediate levels based on strength of preference. Once complete, consistency is checked by examining and confirming the order and relative differences between levels. For example, one may ask if the value difference between level 1 and 2 is truly larger, or smaller, than the value difference between level 2 and 3. The data can then be used to construct a categorical SAVF (Von Winterfeldt & Edwards, 1986).

The difference standard sequence technique is an indifference method utilized when the value measure is either continuous or includes a large number of discrete levels. The SDM is first asked to identify a least preferred level, x_o, and an initial interval, Δ_1 ,that is approximately one-fifth to one-tenth of the overall range. Then values, $v(x_o) = 0$ and $v(x_o + \Delta_1) = v(x_1) = 1$, are assigned arbitrarily. The SDM is then asked to determine additional Δ values such that $v(x_2 - x_1) = v(x_3 - x_2) = ...v(x_i + x_{i-1})$, where $\Delta = x_i - x_{i-1}$. This procedure is repeated until the most preferred level is reached. The delta values are then summed and normalized between 0 and 1. This data obtained can be used to create a piecewise linear function or to conduct a curve fitting operation. In either case the function provides a means to convert the native value measure into units of value through interpolation. Consistency is obtained through the granularity of the initial interval size that is chosen. If the interval is too large the elicitation may be very short, however the interpolation of values not directly assessed may not be accurate. Conversely, if the interval is too small the elicitation may be overly burdensome but would obtain more accurate results (Von Winterfeldt & Edwards, 1986).

The bisection technique is another indifference method utilized when the value measure is continuous or includes a large number of discrete levels. In this technique the most, x^*, and least, x_o, preferred levels of the value measure are determined. Again, $v(x_o) = 0$ and $v(x^*) = 1$ are assigned arbitrarily. The SDM is then asked to determine a level, $x_{.5}$, that obtains a value, $v(x_{.5}) = .5$. This midpoint value can then be used to fit an exponential approximation to the data. This approximation is then checked for consistency by asking the SDM to further subdivide the scale to obtain an $x_{.25}$ and $x_{.75}$ level such that $v(x_{.25}) = .25$ and $v(x_{.75}) = .75$. The elicitation is concluded if the additional points are consistent with the exponential approximation. If not consistent the analyst would choose a different functional form or further subdivide the scale. The goal of this technique is to obtain sufficient data to allow for confident interpolation of all other value scores (Von Winterfeldt & Edwards, 1986).

Step 5: Weight Value Hierarchy

Establishing weight factors for the value hierarchy is the final step in development of the MAVF. The weights are utilized to assess the decision maker's strength of preference among all of the lower level objectives contained in the hierarchy. There are many methods employed for the determination of weight factors including: swing weighting, rank sum, rank exponent, rank reciprocal and rank-order centroid (ROC).

Swing weighting or “trade offs” (Buede, 2000) is an indirect subjective assessment technique in which the SDM ranks the swing values in terms of contribution to the overall value. The swing value is the value obtained from swinging a specific measure from the least preferred level to the most preferred level. The highest (lowest) ranked value is assigned it an arbitrary score of 100 (1). The SDM then determines equal contribution points between all other values and the highest (lowest) ranked values. If swinging the 2^{nd} value measure from the least to most preferred levels provided as much value as swinging the 1^{st} ranked value measure from the least preferred level to a 70% level, then the 2^{nd} value measure would have a weight of 70. This process is repeated for all other value measures, using the highest (lowest) ranked value as an anchor to which all others are compared. The raw weights are then summed and normalized between zero and one (Buede, 2000). This technique requires direct involvement of the decision maker or decision board to perform ranking and weighting determinations.

Rank sum, rank exponent, rank reciprocal and ROC leverage a subjective assessment of the swing ranks of each value to transform the order into swing weights. The SDM is asked to establish a rank order based on “the relative value associated with increasing from the bottom to the top of each value scale” (Buede, 2000). Equation (4), (5), (6), and (7) show the mathematical manipulations required to turn the ranks into weights for the sum, exponent, reciprocal, and ROC methods, respectively (Buede, 2000). These techniques require a lower level of involvement from the SDM and thus can be valuable when access is limited.

(4)

Rank Sum

$$w_i = \left(\frac{k - r_i + 1}{\sum_{j=1}^{k} k - r_j + 1} \right)$$

Where

$k =$ the total number of attributes

$w_i =$ the value weight

$r_i =$ the value rank

(5)

Rank Exponent

$$w_i = \left(\frac{(k - r_i + 1)^z}{\sum_{j=1}^{k} (k - r_j + 1)^z} \right)$$

Where

$k =$ the total number of attributes

$w_i =$ the value weight

$r_i =$ the value rank

$z =$ measure of dispersion

(6)

Rank Reciprocal

$$w_i = \left(\frac{\frac{1}{r_i}}{\sum_{j=1}^{k} \frac{1}{r_j}} \right)$$

Where

$k =$ the total number of attributes

$w_i =$ the value weight

$r_i =$ the value rank

(7)

Rank-Ordered Centroid

$$w_i = \left(\frac{1}{k}\right) \sum_{i=1}^{k} \left(\frac{1}{r_i}\right)$$

$$w_1 = \frac{\left(1 + \frac{1}{2} + \frac{1}{3} + \ldots \frac{1}{k}\right)}{k}$$

$$w_2 = \frac{\left(0 + \frac{1}{2} + \frac{1}{3} + \ldots \frac{1}{k}\right)}{k}$$

$$w_3 = \frac{\left(0 + 0 + \frac{1}{3} + \ldots \frac{1}{k}\right)}{k}$$

Where

$k =$ the total number of attributes

$w_i =$ the value weight

$r_i =$ the value rank

After all the weight factors are determined, they are normalized between 0 and 1. The weights are then multiplied by the associated CVFs in a weighted additive value function. The final MAVF is utilized to calculate the value score for each candidate alternative. The scores can then be ranked or compared on a common scale, allowing the decision maker to make an informed decision (Kirkwood, 1996).

Step 6: Alternative Generation

In the VFT methodology the value structure of the decision maker is considered prior to determining the alternatives for consideration. There are two common problems encountered during alternative generation, too many alternatives or too few alternatives. There are several methods highlighted in the literature to aid in both of these problems (Kirkwood, 1996). In the event of too many alternatives, the decision maker can utilize screening criteria to place firm limits on specific easy to obtain data in an effort to narrow the field of potential alternatives (Keeney, 1992). Additionally, Kirkwood (1996) identifies the concept of dominance, where "an alternative, a_1, dominates a second alternative, a_2, if a_1 is at least as preferred as a_2 with respect to all the attributes and more preferred with respect to at least one attribute" (p. 229). An alternative that is dominated by another alternative, based on the concept described above, can be removed from consideration. In the event of too few alternatives, a strategy generation table can be employed to stimulate creative alternative generation. The strategy generation table lays out the full combinatorial set of decisions enabling decision maker to look for strategies that had previously not been considered (Kirkwood, 1996).

Step 7: Alternative Scoring

At this point in the VFT process, the decision maker has a fully developed model and a set of viable alternatives for consideration. To obtain value scores for each alternative, the decision maker must assess each alternative against all of the quantitative and qualitative value measures established in the model. In some cases this is as simple as pulling a piece of available data such as square footage or miles per gallon. In other cases it requires the decision maker to utilize a constructed scale to establish the score. After all of the alternatives have been scored for each of the value measures, a composite value score can be calculated. The composite value score allows the decision maker to compare alternatives on a best overall value basis or compare all alternatives to established value thresholds.

Step 8: Deterministic Analysis

Deterministic Analysis is the process of calculating value scores from the alternative scoring inputs. To compute the composite value score for each alternative the individual value measure scores and associated weight factors are input into the MAVF. The value scores are then examined to determine relevant conclusions and recommendations. The output of this process is used to communicate the value judgments to the decision maker in Step 10 (Keeney, 1992).

Step 9: Sensitivity Analysis

The sensitivity analysis is completed after the deterministic analysis. The purpose of the sensitivity analysis is to "determine the impact on the ranking of alternatives [from] changes in various model assumptions" (Kirkwood, 1996, p. 82). The sensitivity analysis provides the decision maker with a sense of model strength or robustness. For example, sensitivity analysis could identify if the alternative rankings produced by the model would change given slight variations in the decision maker's subjective weight factor determination. If this were the case, the decision maker should be aware of this sensitivity and ensure that the weight factors were accurate before proceeding with the recommended alternative.

Step 10: Conclusions & Recommendations

The final step of the VFT model development process is to provide conclusions and recommendations to the decision maker. This is a fairly straight forward concept. In this stage the analyst would gather the data and analysis to build a summary level document or section explaining the conclusions of the decision analysis effort. This document or section would include recommendations and any points of clarification or sensitivities of the model.

Uncertainty in Multiattribute Decision Model

At the beginning of Chapter 2, it was stated that the two primary contributors that make decisions complex are uncertainty and multiple conflicting objectives (Keeney & Raiffa, 1993)(Von Winterfeldt & Edwards, 1986). Interface decisions with multiple objectives under the assumption of certainty is the focus of this research. However, the addition of uncertainty could enable the model better match reality. This section will discuss important terminology and then explore two approaches for handling uncertainty in decision scenarios with multiple objectives. Finally, strengths and weaknesses of each approach are outlined.

Understanding the difference between value and utility is a critical concept to decision analysis practitioners. The terms value and value function are explained in Table 3. Table 5 captures explanations of utility and utility functions. Matheson and

Abbas describe two primary approaches for coalescing a decision maker's trade-off preferences and risk preferences to compare alternatives (2005). The approaches are discussed below.

Table 5: Utility Theory Terminology

Term	Description
Utility	Concerned with capturing a "decision maker's attitude toward risk-taking" (Parnell et al., 2013, p. 56).
Utility Function	"A mapping of the utility metric from the value metric in the case of a single-dimensional utility function or from all of the performance scores in the case of a multidimensional utility function" (Parnell et al., 2013, p. 56).

Approach 1: The "Standford School approach" (Matheson & Abbas, 2005, p. 229) depicted in Figure 6, leverages a multidimensional value function to capture all trade-off preferences which converts all component value measures into a single 'value' metric. After the multidimensional value function is established, a single-dimensional

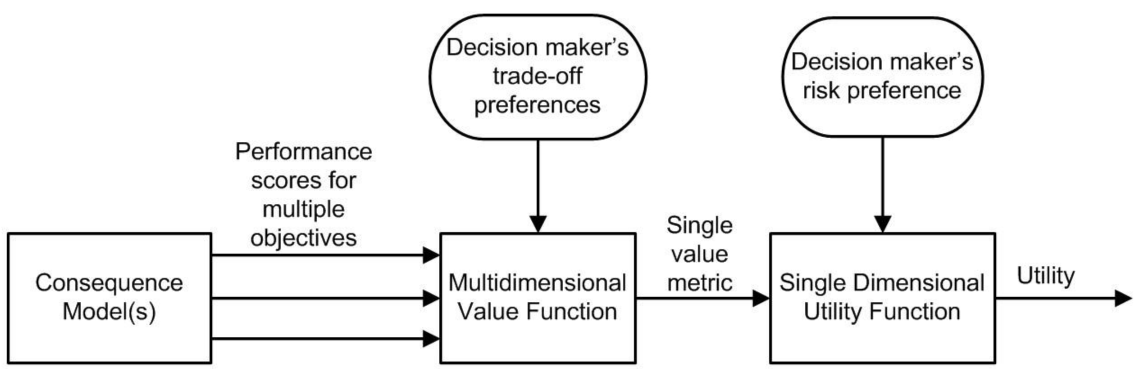


Figure 6: Approach 1 (Parnell et al., 2013, p. 59)

utility function, capturing the decision maker's risk preferences over the single value metric, can be constructed. The end result is a single utility metric for each alternative (Parnell et al., 2013).

Approach 2: The “Keeney-Raiffa approach” (Matheson & Abbas, 2005, p. 229) depicted in Figure 7, employs a Multidimensional utility function which captures both trade-off and risk preferences. This approach leverages the assumption or verification of independence conditions to simplify the functional form of the utility function and expedite the elicitation process. Like Approach 1, the end result is a single utility metric for each alternative that can be used for objective comparison (Parnell et al., 2013).

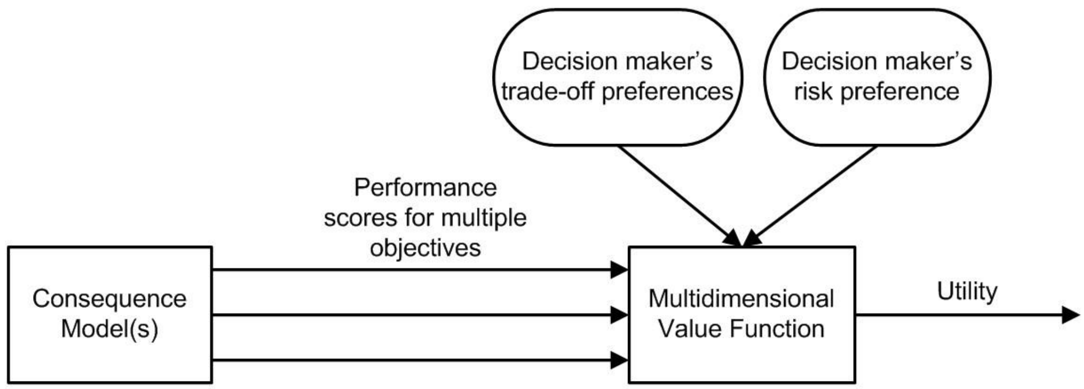


Figure 7: Approach 2 (Parnell et al., 2013, p. 59)

Both approaches share the same goal: provide objective criteria for comparing alternatives in support of decision making. Approach 1 is regarded as easier to implement because the bulk of the elicitation is focused on developing a deterministic value function. Additionally, if the SDM is risk neutral or the decision is low risk the second step can be removed (Parnell et al., 2013). Finally, Approach 1 captures utility dependence without the elicitation complexity associated with the multidimensional utility function employed by Approach 2 (Matheson & Abbas, 2005). A weakness of Approach 1 is the use of a unit-less value metric which makes intuitive construction of a utility function over the value metric difficult (Keeney & Raiffa, 1993). Approach 2 has the benefit of a single step, simple utility function, and a straightforward elicitation process if the independence conditions are verified or assumed (Parnell et al., 2013). However, in many cases the independence conditions do not hold and making the assumption that they do hold ignores potentially important interactions (Matheson & Abbas, 2005).

Summary

Chapter 2 provided an overview of literature in the areas of open systems and decision analysis. First, the areas of MOSA in the systems engineering process, MOSA policy, and MOSA guidance were described. Next, two decision analysis methods, the AHP and VFT, were examined followed by a detailed exploration of the execution of the VFT decision model development process. Finally, Chapter 2 concluded with an exploration of methods of incorporating uncertainty into multiattribute decision models.

III. Methodology

Chapter 3 follows the VFT process discussed in Chapter 2, beginning with justification of VFT selection followed by discussion of problem formulation. Next, the method by which data was collected and aggregated into a hierarchy that represents the preference structure of the SDM is addressed. Following the discussion of hierarchy construction, this chapter describes methods by which value measures, value functions, and weight factors were determined. Finally, the results of a hierarchy quality evaluation are explained. Chapter 2 indicates several additional steps beyond value hierarchy weighting. Alternative Generation, Alternative Scoring, Deterministic Analysis and Sensitivity Analysis will be discussed in Chapter 4. Conclusions and Recommendations are captured in Chapter 5.

Methodology Selection

The Medium Altitude UAS System Program Office has the challenge of integrating many subsystems into the Predator and Reaper UAS. This requirement highlights the need for a defensible, repeatable, and objective evaluation framework to support making IIM decisions while considering technical and programmatic factors. The program office considers multiple criteria in the choice of IIMs for the many interfaces employed in a UAS. Each new interface requires a new evaluation though the quantity of potential IIMs is small and the relevant evaluation factors remain constant. This research is focused on building a deterministic evaluation framework to ensure accurate and consistent choices that reflect the SDMs value structure while not requiring direct involvement in every evaluation. VFT was chosen over AHP because literature indicated that it is better suited for repeated decisions and, after constructed, VFT models were usable in the absence of the SDM (Belton, 1986). VFT was used to construct an evaluation framework consistent with the values of the program office with respect to IIMs.

Step 1: Problem Identification

As discussed in Chapter 2, the goal of the problem identification step is to gain a complete and contextually accurate understanding of the problem. Complete understanding of the IIM problem was established through an amalgamation of three sources: the author's personal experiences, DoD acquisition directives, and interviews with SDMs in the program office. The author's experience is in the area of payload integration with UAS showed that many IIM decisions were entrusted to the contractor due to schedule urgency. Abdicating responsibility for IIM decisions to the contractor resulted in closed interfaces that required constant change which generated challenges for system integration, system support and technology evolution. Research in interface integration revealed that DoD Directive 5000.01 states "a modular, open-systems approach shall be employed, where feasible" (Office of the Undersecretary of Defense for Acquisition Technology & Logistics, 2007). Interviews with SDMs from the program office clarified the problem. By definition, implementation of open interfaces is always feasible, but it isn't always practical or reasonable. The issue of practicality includes factors other than technical performance. Contextual elements of the decision frame such as schedule urgency, cost, interface utilization and classification needed to be considered when determining the practicality of implementing an open interface. The three sources listed above lead to the conclusion that DoD acquisition lacks a defensible, repeatable, and objective method for determining if implementing a modular, open-systems approach is appropriate for a specific interface. The OSJTF reinforced this finding when it stated that “key interfaces should be examined very carefully to insure that the use of an open standard is both feasible and appropriate based on performance and business objectives” (2004).

To develop the MQ-1/MQ-9 value structure with respect to IIMs, Gold and Silver standard sources were employed resulting in a set of 76 decision factors, Table 6. Gold standard documentation was examined to gain contextual understanding of values related to open interfaces. The OSJTF Program Manager’s Guide was consulted to provide understanding of doctrinal based decision factors. Journal articles and conference submittals in the areas of open system integration and evolutionary acquisition were examined for additional factors. In an acquisition program office, IPT members, in the areas of Program Management, Engineering, Logistics, Operations, Contracting and Finance, would advise the SDM on program decisions. To capture this dynamic, interviews were conducted with members the IPT. The research and interviews resulted in a comprehensive list of 76 factors providing a foundation for hierarchy development.

Table 6: Decision Factor List

	Decision Factor	Source
1	Mutability of the connected systems	(Dillard & Ford, 2007)
2	Logistics support plan	
3	Time criticality of future iterations / development of tenant systems	
4	Cycle time between phases or upgrades	
5	Amount of interdependency between systems… effect of one systems evolution on another	
6	Evolving technologies	(Ford & Dillard, 2008)
7	Use of legacy hardware	
8	Need for flexibility in acquisition to manage uncertainty in technology	
9	New challenges that are difficult to forecast	
10	Need for interoperability	
11	Integration with joint services	
12	Collaboration with allies	
13	Need for rapid acquisition response	
14	Evolving Technologies	(Ford & Dillard, 2009)
15	Evolving Programmatic / Acquisition Environment	
16	Changing Acquisition Environment	
17	Continuous improvement required	
18	Changing threat matrices	
19	New Challenges/Evolving threats that are difficult to forecast	
20	Dynamic Threat	
21	Ability to disclose design information	
22	Joint/allied interactions with the system interface	
23	Constrained funding	
24	Little flexibility in money for development	
25	Short capability improvement cycle times	
26	System in urgent need of improvement	
27	Requirement for rapid evolutionary improvement	
28	Little flexibility in time for development	
29	Rate of iteration	

30	Leverage of COTS components	(OSJTF, 2004)
31	Potential for technology obsolescence	
32	Changing Requirements	
33	Use of common or cross platform components	
34	Development urgency – need for reduced development timelines	
35	Multiple sources of supply for a host or tenant	
36	Competition between vendors	
37	Frequency of configuration changes in tenant systems (Stability of Tenant Systems)	(IPT Engineering, personal communication, September 12, 2013)
38	Frequency of configuration changes in host system (Stability of Host System)	
39	Volatility/Stability of industry use of the open standard	
40	Maturity of the open standard	
41	Availability of open standards	
42	Security classification of interface description or mechanism	
43	Users of the interface (Quantity)	
44	Number of instances of the interface on a given platform	
45	Sources of tenants	
46	Predictability of changes at the interface	
47	Complexity of the Interface	
48	Will the interface decision restrict future competition	(IPT Contracting, personal communication, September 13, 2013)
49	Frequency of system changes at the interface	(IPT Program Management, personal communication, September 13, 2013)
50	Interface proliferation (the use of the interface on coupled systems)	
51	The number of open standards that exist that could do the job	
52	Proprietary nature of ultra high performance systems	
53	Level of system security required	
54	Number of users of the interface	
55	Capability (Training Level) of the maintenance crew	
56	Time available to perform a repair and replace	
57	Maintenance Environment	
58	Amount of change and availability of funding	
59	Interfacing experience of the integrator	
60	Urgency of capability implementation as a function of time required to implement an open interface	

61	Change to coupled systems	(IPT Logistics, personal communication, September 17, 2013)
62	Training level of personnel	
63	Maintenance concept	
64	Urgency of repair	
65	Frequency remove/replace at the interface	
66	System stability (effect of technological change)	(IPT Finance, personal communication, September 19, 2013)
67	Stability of the intended interface standard	
68	Ease of maintenance desired/required	
69	Desired/required training level for maintenance Personnel	
70	Cost of development/implementation of the standard	
71	Competition	
72	Failure rate of the interface	
73	Mission disparity	(IPT Operations, personal communication, October 3, 2013)
74	Security level of associated equipment	
75	Urgency of development	
76	Complexity of system integration	

Step 2: Create Value Hierarchy

The full factor list found during problem identification was used in an affinity diagram, aggregation and sorting exercise, using Microsoft Excel, to group and categorize similar factors. The factors were then organized into in a comprehensive hierarchy, Figure 8. Platinum standard inputs were used to confirm and refine the hierarchy.

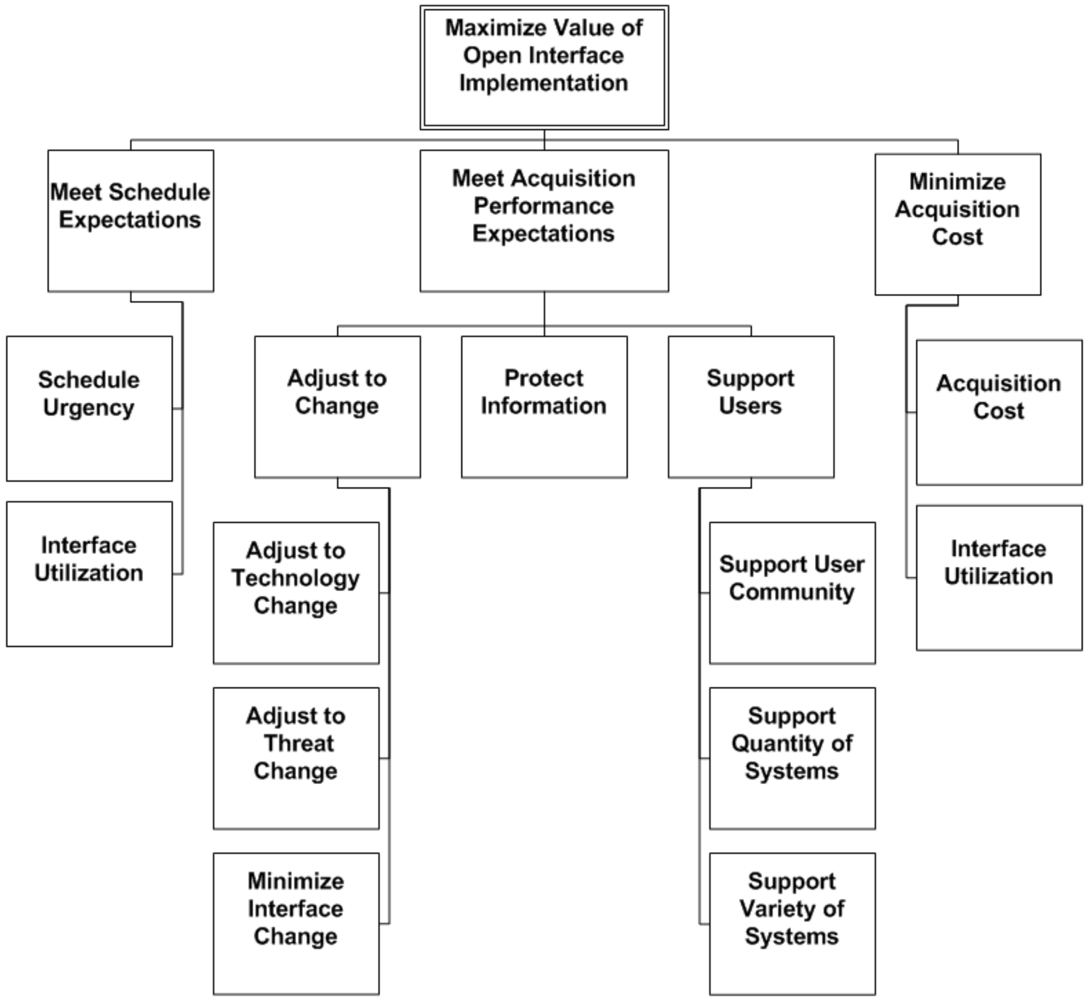


Figure 8: IEF Value Hierarchy

Value Hierarchy Description

The strategic objective of the hierarchy was to maximize the value of an open interface implementation. This strategic objective was decomposed into three fundamental objectives: Minimize Acquisition Cost, Meet Schedule Expectations, and Meet Acquisition Performance Expectations. Minimize Acquisition Cost assesses the cost of implementing open as compared to closed with consideration of the number integrations at the interface. Meet Schedule Expectations addresses the issue of schedule pressure for capability integration at the interface. Meet Acquisition Performance Expectations considers those interface performance and contextual factors other than cost and schedule. The following are descriptions of lowest level values within the meet acquisition performance expectations branch:

<u>Adjust to Change</u>: Captures the interface performance and contextual factors related to change. The value of an open interface is related to both the maturity of the interface and the amount of change that will occur at the interface. This value is broken into three sub values:

Adjust to Technology Change: This value addresses the volume of change driven by technology alteration or maturation.

Adjust to Threat Change: This value addresses the volume of change driven by changing adversary tactics.

Minimize Interface Change: This value refers to the maturity of the interface selected. If the interface option that is available is of a low maturity level it would be of limited value to the program because it would likely require modification.

<u>Protect Information</u>: Captures the need to protect information about the capabilities of connected systems at the appropriate level. Making an interface open implies a willingness to share information about the interface. This sharing could inadvertently provide information about the capability of a system connected at the interface. Thus, highly protected systems would limit the value of openness.

<u>Support Users</u>: Captures the interface performance factors associated with ensuring the organizations and systems that utilize the interface are supported. This value is broken into three sub values:

Support User Community: This value addresses the need of the interface to support the using community. A highly varied using community would increase the value of an open interface.

Support Quantity of Systems: This value addresses the need of the interface to support multiple functionally equivalent systems. For the purposes of this research, two systems are deemed functionally equivalent if they are used to meet the same requirement. It is not the performance of the systems that is compared but the requirements to which they are held.

Support Variety of Systems: This value addresses the need of the interface to support multiple functionally different systems. For the purposes of this research two systems are functionally different if they are used to meet different requirements.

Step 3 and 4: Evaluation Measures and Value Functions

Upon completion of the value hierarchy, evaluation measures were established using silver and for each of the lowest level hierarchical elements. The goal is to provide a means of objectively measuring each alternative against all of the values using scales that are easily understood by the intended audience. Silver and platinum standard inputs were used to choose value measures and contstruct the component value functions. The measures employed were both direct and proxy using both natural and constructed scales. After the measures were established, value functions were developed for each value to establish a single common scale. Categorical, exponential, piecewise linear and multilinear value functions were employed. All evaluation measures and value functions are described below.

Adjust to Technology Change: This value is measured using a negatively oriented, categorical, natural proxy scale of the Technology Readiness Level (TRL) of connected systems to assess the amount of technology change that will occur at the interface. Because more than one system can be connected to an interface an average of the TRLs of the connected systems is utilized. The use of an average captures intermediate levels of TRL rather than applying a rounded score. While this more accurately captures the amount of change at the interface it requires the use of continuous function rather than a categorical function. There is an inverse relationship between TRL and technology change. A high TRL indicates the systems connected at the interface are very mature and thus would have little technology change. The maximum value for an open interface is associated with a TRL 5 while TRL 9 receives the lowest value. The TRL scale is shown in Table 7. TRLs 1 through 4 were not included because technology of this maturity would not be considered for integration.

Table 7: Technology Readiness Level (X_1)(Assistant Secretary of Defense for Research and Engineering (ASD (R&E)), 2011)

TRL 5	"Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components."
TRL 6	"Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a highfidelity laboratory environment or in a simulated operational environment."
TRL 7	"Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an air-craft, in a vehicle, or in space)."
TRL 8	"Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications."
TRL 9	"Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions."

Technology change was represented by the piecewise linear function captured with equation (8) and shown in Figure 9. The piecewise linear function was chosen because it was able to capture an inflection point in the value function at average TRL 7.2 described by the decision maker.

(8)

$$v_1(x_1) = \begin{cases} -0.1 \cdot x_1 + 0.9 & \text{for} \quad 8 < x_1 \le 9 \\ -0.5 \cdot x_1 + 4.1 & \text{for} \quad 7.2 < x_1 \le 8 \\ -0.\overline{333} \cdot x_1 + 2.9 & \text{for} \quad 6 < x_1 \le 7.2 \\ -0.1 \cdot x_1 + 1.5 & \text{for} \quad 5 \le x_1 \le 6 \end{cases}$$

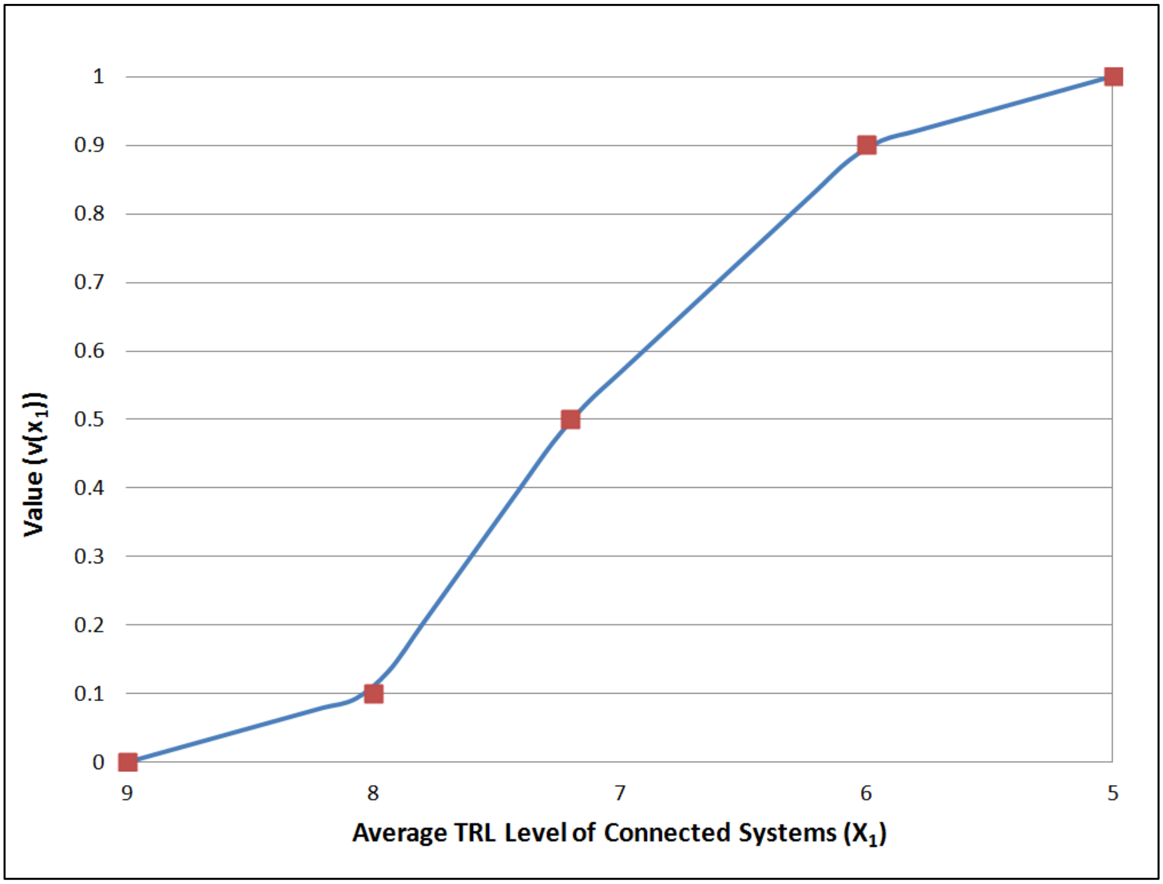


Figure 9: Adjust to Technology Change Value Function

Adjust to Threat Change: This value employs a positively oriented constructed direct scale measuring the threat environment to assess the amount of change that will occur at the interface due to changing adversary tactics. Multiple adversaries with changing tactics drive a high level of change which results in a high value for an open interface. The lowest value for an open interface is associated peace time which is associated with the most consistent tactics. The threat environment scale is shown in Table 8.

Table 8: Threat Environment (X_2)

5	**Multiple Adversaries w/ Changing Tactics**
4	**Single Adversary w/ Changing Tactics**
3	**Multiple Adversaries w/ Consistent Tactics**
2	**Single Adversary w/ Consistent Tactics**
1	**Peace Time**

Threat change was represented by the categorical function captured with equation (9) and shown in Figure 10. The categorical function was chosen because there were a small number of discrete levels in the scale enabling the use of direct assessment by the decision maker.

$$v_2(x_2) = \begin{cases} 0 & \text{for } x_2 = 1 \\ 0.2 & \text{for } x_2 = 2 \\ 0.75 & \text{for } x_2 = 3 \\ 0.75 & \text{for } x_2 = 4 \\ 1.0 & \text{for } x_2 = 5 \end{cases} \tag{9}$$

Figure 10: Adjust to Threat Change Value Function

Minimize Interface Change: This value is assessed with a positively oriented constructed direct scale measuring the maximum maturity of the interfaces available for implementation. A well-documented interface where change occurs in a controlled manner is of the most value. Conversely, an undocumented interface where change occurs at the discretion of a single organization or integrator is of the least value. The threat environment scale is shown in Table 9. Interface change was represented by the categorical function captured with equation (10) and shown in Figure 10. The categorical function was chosen because there were a small number of discrete levels in the scale enabling the use of direct assessment by the decision maker.

Table 9: Interface Maturity Level (IML) (X_3)

4	Standards Exist and are documented by a standards management organization. Change occurs in a controlled manner, with rigorous review and community approval
3	Interface is documented by a program office through an interface control document or equivalent. Change is controlled by a program office
2	There are no formally documented standards, however there is industry agreement. Change occurs through industry consensus.
1	There is no defined standard and there appears to be no agreement among integrators. Changes are dictated by each integrator.

(10)

$$v_3(x_3) = \begin{cases} 0 & \text{for} \quad x_3 = 1 \\ 0.15 & \text{for} \quad x_3 = 2 \\ 0.5 & \text{for} \quad x_3 = 3 \\ 1.0 & \text{for} \quad x_3 = 4 \end{cases}$$

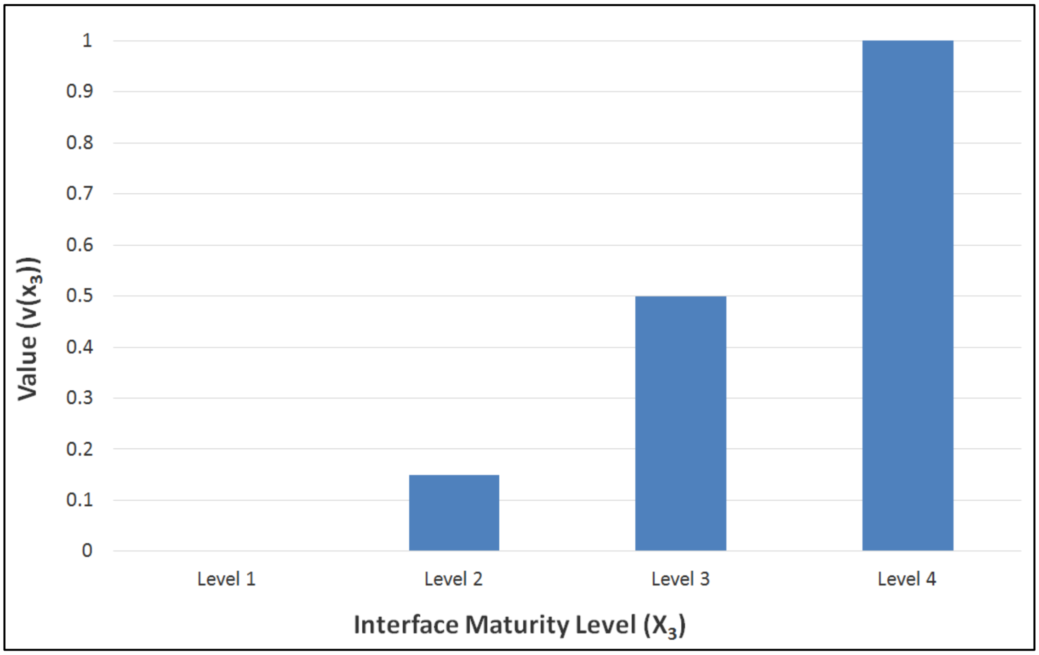


Figure 11: Minimize Interface Change Value Function

Protect Information: This value is measured using a negatively oriented natural direct scale assessing the maximum information protection level (IPL) required for connected systems. Utilization of an open interface implies that a willingness to share information about the interface exists. An inverse relationship between the IPL and the value of an open interface exists. As the IPL of connected systems increases the willingness to share and, subsequently, the value of an open interface decreases. The maximum value for an open interface is associated with an unclassified IPL. The minimum value is associated with a compartmentalized top secret IPL. The IPL scale is shown in Table 10. Information protection was represented by the categorical function

Table 10: Information Protection Level (X_4)

5	**Compartmentalized TS**
4	**Top Secret**
3	**Secret**
2	**Controlled Unclassified**
1	**Unclassified**

captured with equation (11) and shown in Figure 12 below. The categorical function was chosen because there were a small number of discrete levels in the scale enabling the use of direct assessment by the decision maker.

$$v_4(x_4) = \begin{cases} 1.0 & \text{for } x_4 = 1 \\ 0.75 & \text{for } x_4 = 2 \\ 0.4 & \text{for } x_4 = 3 \\ 0.1 & \text{for } x_4 = 4 \\ 0 & \text{for } x_4 = 5 \end{cases} \tag{11}$$

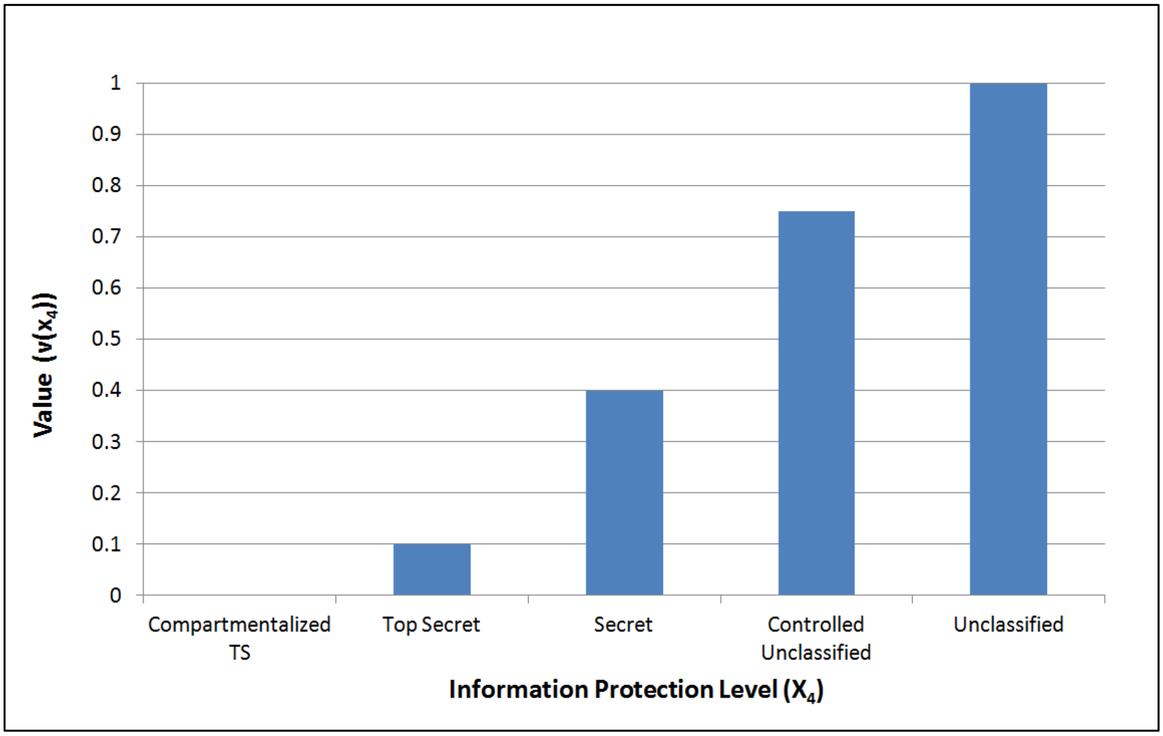


Figure 12: Protect Information Value Function

Support User Community: This value employs a positively oriented constructed direct scale assessing the user community that will interact with the interface. As the diversity of the user community increases the value of an open interface increases. The maximum value is associated with a multi-national community with no limitations on sharing. Conversely a single unit user community receives the least value. The user community scale is shown in Table 11. User community support was represented by the categorical function captured with equation (12) and shown in Figure 12. The categorical function was chosen because there were a small number of discrete levels in the scale enabling the use of direct assessment by the decision maker.

Table 11: User Community of Connected Systems (X_5)

6	**Multi-Nation (Not Limited)**
5	**Multi-Nation (Allied Only)**
4	**Multi-Service**
3	**Single Service**
2	**Single MAJCOM**
1	**Single Unit**

$$v_5(x_5) = \begin{cases} 1.0 & \text{for} \quad x_5 = 6 \\ 0.65 & \text{for} \quad x_5 = 5 \\ 0.5 & \text{for} \quad x_5 = 4 \\ 0.25 & \text{for} \quad x_5 = 3 \\ 0.2 & \text{for} \quad x_5 = 2 \\ 0 & \text{for} \quad x_5 = 1 \end{cases} \qquad \textbf{(12)}$$

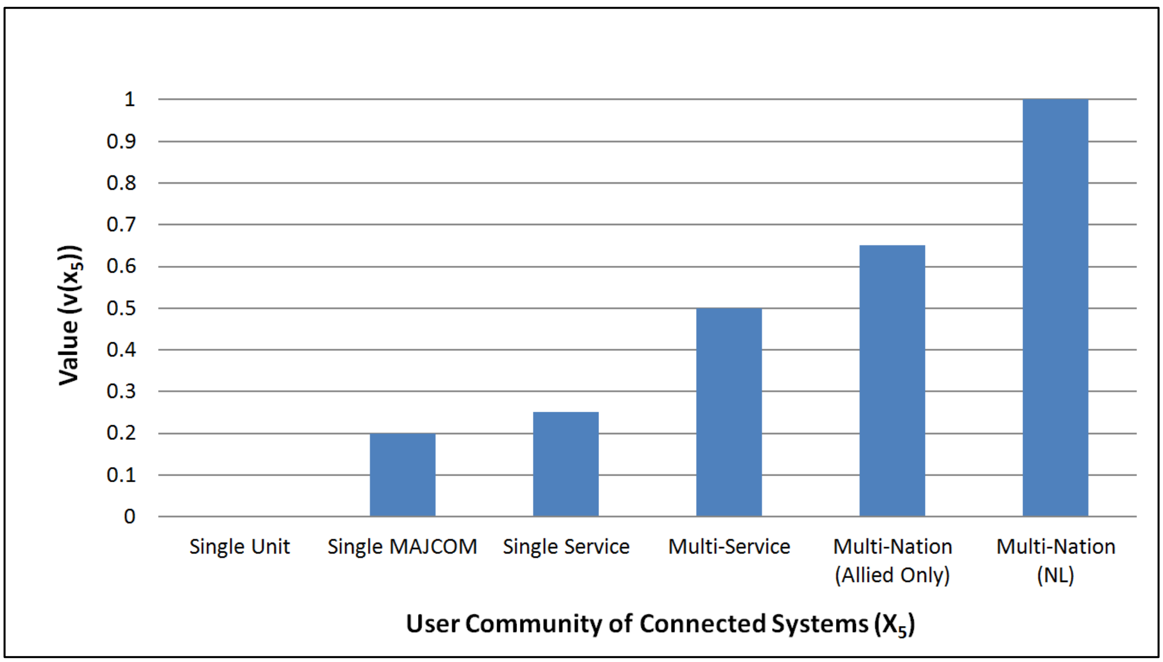


Figure 13: Support User Community Value Function

Support Quantity of Systems: This value is assessed with a positively oriented natural direct scale measuring the quantity of functionally equivalent systems that connect at the interface. The MQ-1 and MQ-9 employ both small quantity high value systems as well as readily available commercial off-the-shelf (COTS). The COTS systems drive the maximum for this scale. A use case was developed for a monitor installed in the ground station with the requirements of 22in diagonal viewing angle, and aspect ratio of 16:9. This resulted in 38 functionally equivalent systems. To establish the maximum of 50, ~32% was added to the number found in the use case to provide margin for other COTS systems. The small quantity high value systems drive the minimum of one for this scale. It is common that a system is developed specifically to meet a set of requirements and thus only 1 functionally equivalent system exists. The quantity of systems was represented by an exponential function captured with equation (13). The bisection method was utilized to elicit information shown in Table 12. The exponential function was then fit to those points as shown in Figure 14.

$$v_6(x_6) = \begin{cases} 1 & \text{for} \quad x_6 > 50 \\ \dfrac{1-e^{-0.25\cdot(x_6-1)}}{1-e^{-0.25\cdot(50-1)}} & \text{for} \quad 1 \le x_6 \le 50 \\ 0 & \text{for} \quad x_6 < 1 \end{cases} \tag{13}$$

Table 12: Quantity of Systems Elicited Information (X_6)

	Value	Attribute Measure
x^*	1	50
$x^{.75}$	0.75	8
$x^{.5}$	0.5	3
$x^{.25}$	0.25	2
x^0	0	1

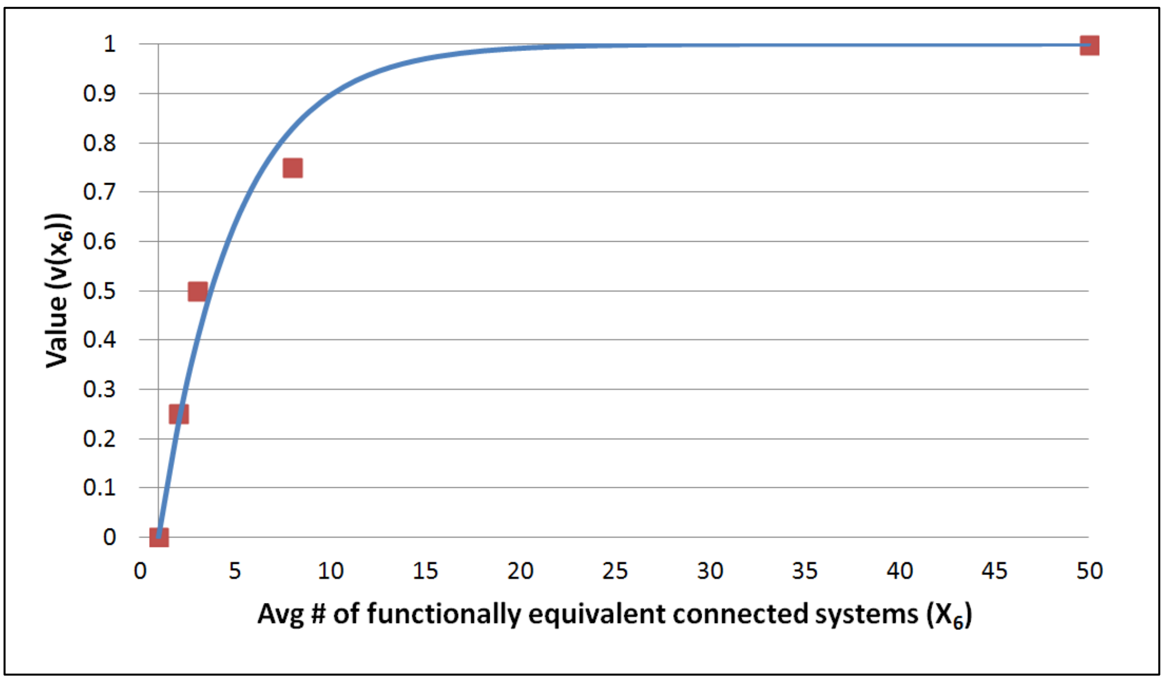


Figure 14: Support Quantity of Systems Value Function

Support Variety of Systems: This value is measured using a positively oriented natural direct scale measuring the quantity of functionally different systems that connect at the interface. The F-16 external storage mechanical interface was examined to establish a reasonable maximum for the scale. This aircraft was chosen because it shares a similar mission to the MQ-1 and MQ-9 and has been in service much longer. It is assumed that, because of the service longevity, the number of functionally different connected systems has reached a maximum. There were three categories of systems that connected to the interface: munitions, podded sensors, and fuel tanks. There were seven different munitions connected at the interface (F-16 Armament). Six podded sensor types were identified by the decision maker. A single fuel tank was assumed by the author. This accounted for 14 functionally different connected systems. To establish the maximum of 20, ~43% was added to account for classified integrations. The minimum was established as one because there must be at least one connected system for an interface to exist. The variety of systems was represented by an exponential function captured with equation (14). The bisection method was utilized to obtain the information shown in Table 13. The exponential function was then fit to those points as shown in Figure 15.

(14)

$$v_7(x_7) = \begin{cases} 1 & \text{for} \quad x_7 > 20 \\ \dfrac{1 - e^{-0.1621\cdot(x_7 - 1)}}{1 - e^{-0.1621\cdot(20-1)}} & \text{for} \quad 1 \le x_7 \le 20 \\ 0 & \text{for} \quad x_7 < 1 \end{cases}$$

Table 13: Variety of System Elicited Information (X_7)

	Value	Attribute Measure
x^*	1	20
$x^{.75}$	0.75	8
$x^{.5}$	0.5	5
$x^{.25}$	0.25	3
x^0	0	1

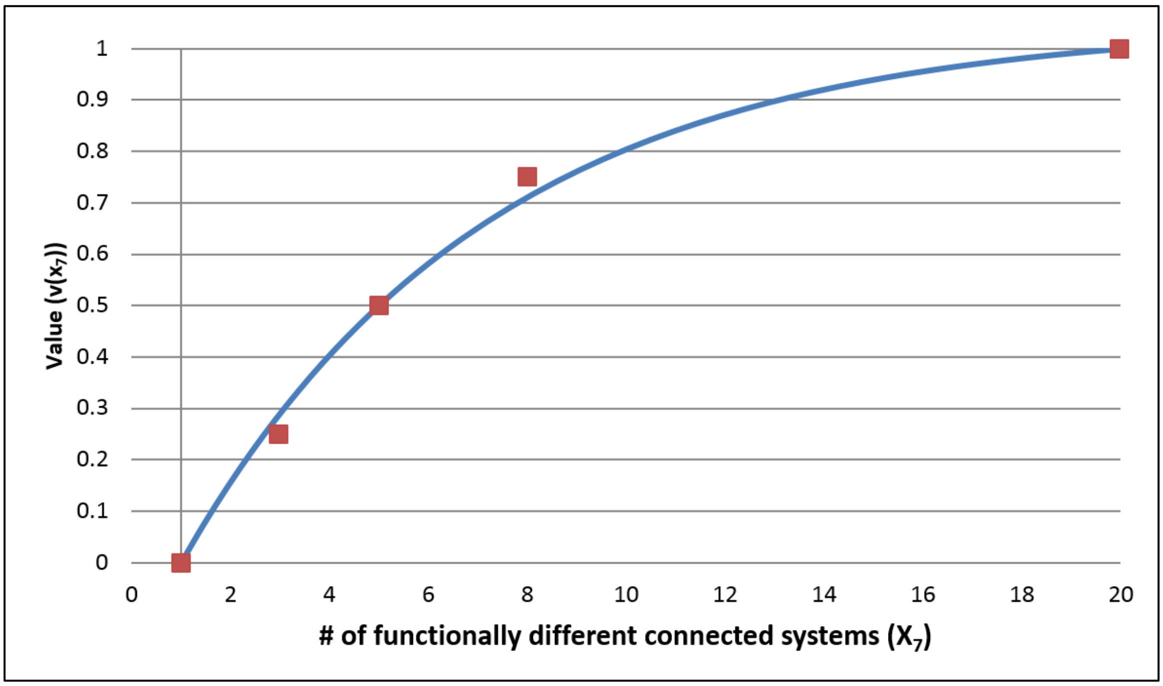


Figure 15: Support Variety of Systems Value Function

Minimize acquisition cost: This value employs a multilinear value function with a complementary relationship between attributes. The multilinear value function is employed to capture an interaction between the cost of implementing an open interface and the number of integrations for which that interface will be used. The two scales employed to construct the multilinear function were the cost differential (X_8) between an open and closed interface implementation, and the number of integrations (X_9) over the planning horizon. Measuring cost differential as a ratio was chosen over measuring cost directly because it avoided issues with time value of money and allowed for direct comparison between interface implementations regardless of acquisition cost. The maximum of an open interface implementation cost equal to double the closed interface implementation cost was chosen based on recommendation by the SDM. The number of integrations employs a positively oriented natural direct scale. The maximum was established based on two integrations at the interface per year through the 10 year planning horizon for a total of 20 integrations. It is assumed that the interface exists and thus has one connected system. The minimum, zero integrations, indicates that no new systems will be integrated to the interface over the planning horizon. The multilinear representation of minimizing acquisition cost is shown in equation (15). To simplify the elicitation, linear conditional value functions scaled between 0 and 1 were assumed. The scaling constants s_8, s_9, and s_{89} were determined through structured discussions using an Excel-based iso-preference tool (Robbins, 2013). As can be seen in Figure 16, a series of points were determined throughout the two attribute value space to support scaling constant determination. The maximum value of one is achieved when there are 20 integrations and a zero cost differential. The lines separating colors indicate

(15)

$$v_{89}(x_8, x_9) = s_8 \cdot v_8(x_8) + s_9 \cdot v_9(x_9) + s_{89} \cdot v_8(x_8) \cdot v_9(x_9)$$

Where

Cost Differential: $v_8(x_8) = 1 - x_8$

$$x_8 = \begin{cases} 0 & \text{for OI Cost} < \text{CI Cost} \\ \dfrac{\text{OI Cost} - \text{CI Cost}}{\text{CI Cost}} & \text{for CI Cost} \le \text{OI Cost} \le 2 \cdot \text{CI Cost} \\ 1 & \text{for OI Cost} > 2 \cdot \text{CI Cost} \end{cases}$$

OI Cost=The Cost to Implement an Open Interface
CI Cost=The Cost to Implement a Closed Interface
Lower cost differential is preferred

And

# of Integrations: $v_9(x_9) = \dfrac{x_9}{20}$

indifference. Any point along the indifference line indicated indifference for the decision maker. The shape of the iso-preference curves are driven by the scaling constants, determined through the iterative process shown in Figure 17, which were applied to the value function. This process was repeated until the preferences depicted in the tool were consistent with the preferences of the SDM. The multilinear value function for minimizing acquisition cost is shown in equation (16).

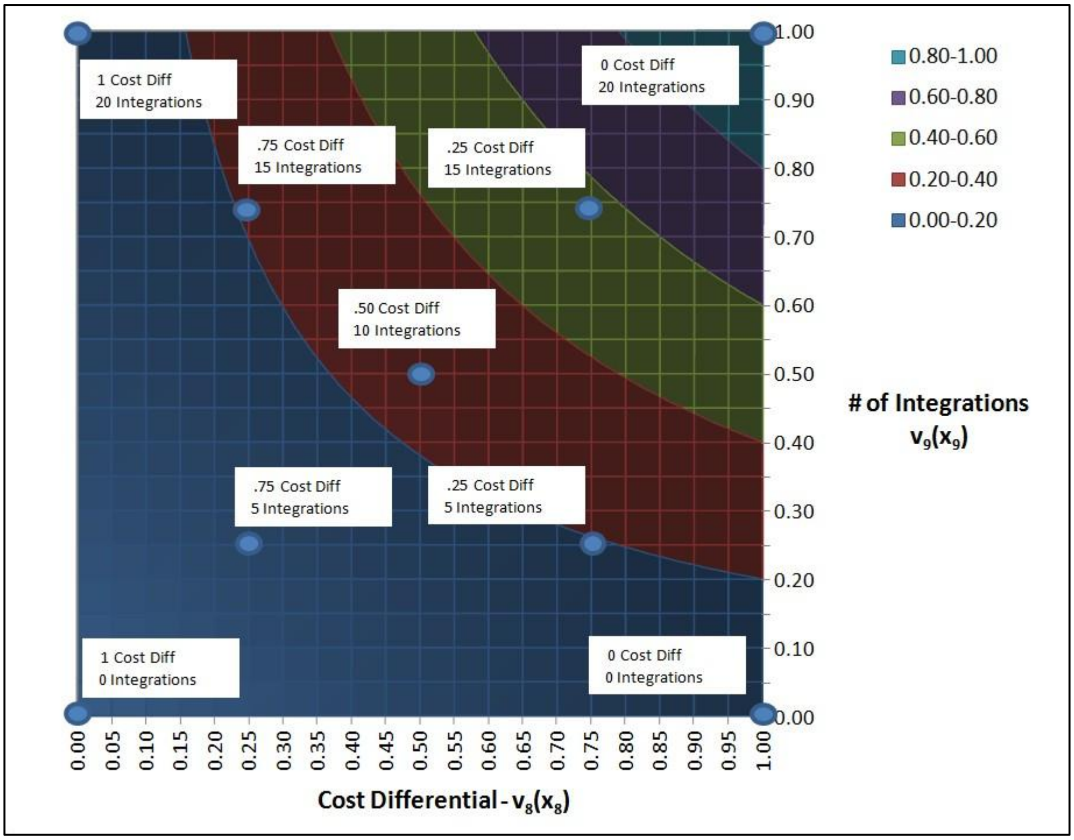


Figure 16: Minimize Acquisition Cost Iso-Preference Curves

$$v_{89}(x_8, x_9) = 0.0 \cdot (1 - x_8) + 0.05 \cdot \left(\frac{x_9}{20}\right) + 0.95 \cdot (1 - x_8) \cdot \left(\frac{x_9}{20}\right) \quad \textbf{(16)}$$

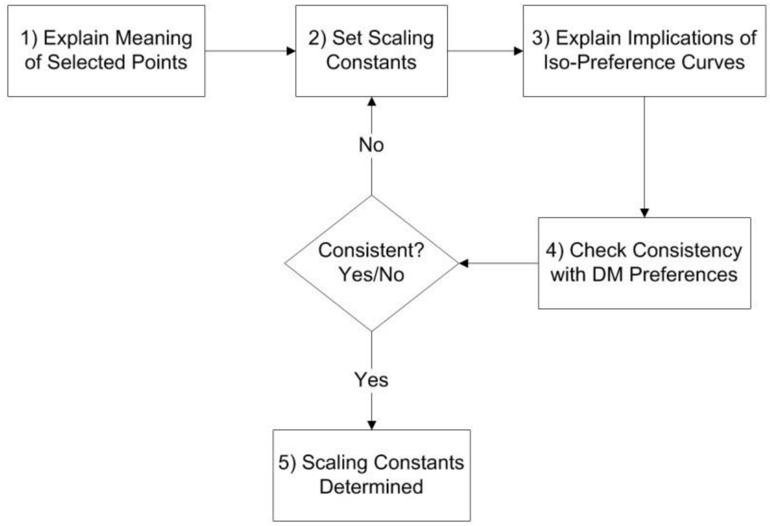


Figure 17: Iterative Multilinear Scaling Constant Determination Process

Meet schedule expectations: This value employs a multilinear value function with a complementary relationship between attributes. The multilinear value function was employed to capture an interaction between schedule urgency (X_{10}) and the number of integrations (X_{11}) for which that interface will be used. Schedule urgency was measured using a positively oriented constructed proxy scale shown in Table 14, which measures

Table 14: Schedule Urgency of Integrations (X_{10})

6	Nationally Driven
5	Department of Defense Driven
4	United States Air Force Driven
3	MAJCOM Driven
2	Unit Driven
1	Not Mission Driven

mission priority for integration efforts at the interface. The scale for the number of integrations is duplicated from that used in the value function for minimizing acquisition cost. Linear conditional value functions scaled between 0 and 1 were assumed to the simplify the elicitation. Figure 18 shows the points throughout the two attribute value space that were used to determine the scaling constants, s_{10}, s_{11}, and s_{1011}. The maximum value of one is achieved when there are 20 integrations and a level six schedule urgency. The iterative process detailed in Figure 17, was employed to determine the scaling constants used in the multilinear value function for schedule urgency shown in equation (17).

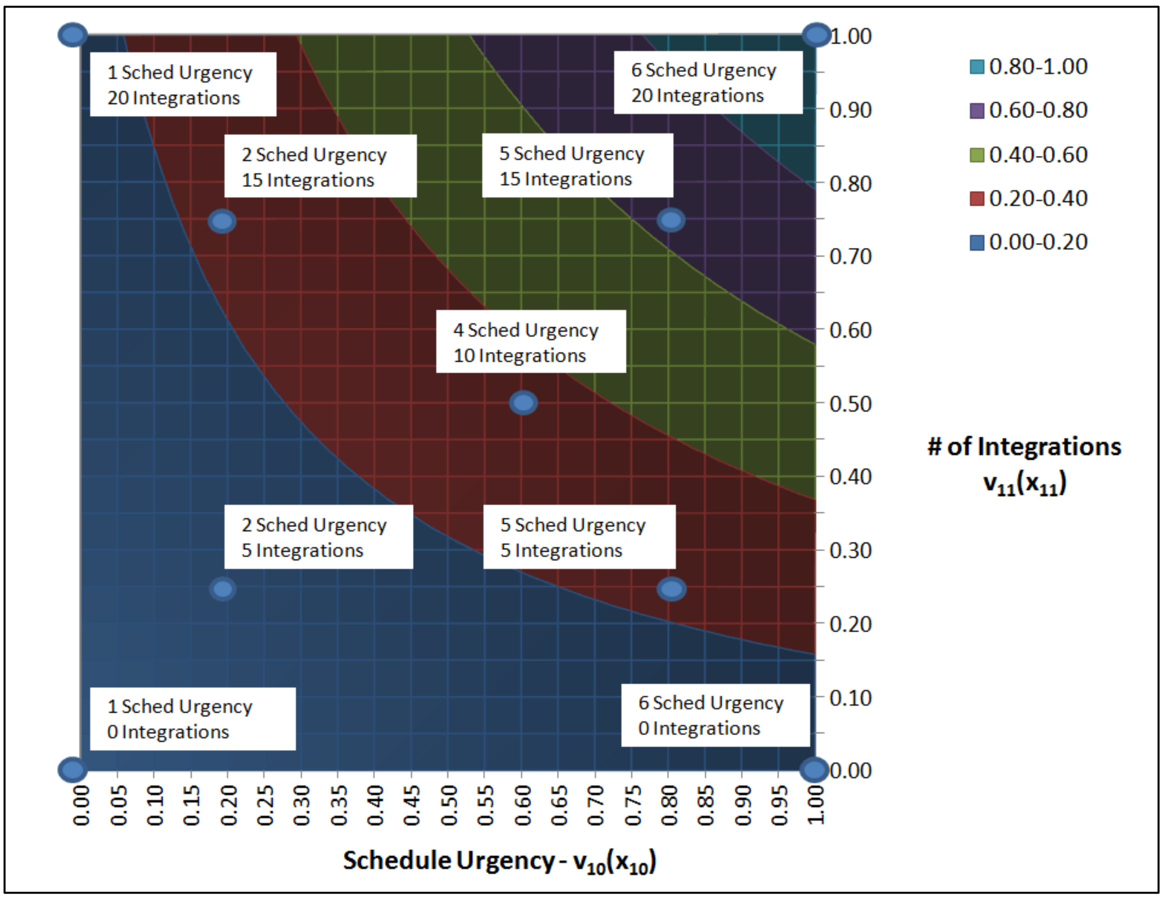


Figure 18: Meet Schedule Expectations Iso-Preference Curves

(17)

$$v_{1011}(x_{10}, x_{11}) = s_{10} \cdot v_{10}(x_{10}) + s_{11} \cdot v_{11}(x_{11}) + s_{1011} \cdot v_{10}(x_{10}) \cdot v_{11}(x_{11})$$

Where

Schedule Urgency: $v_{10}(x_{10}) = \dfrac{x_{10} - 1}{5}$

And

# of Integrations: $v_{11}(x_{11}) = \dfrac{x_{11}}{20}$

$$v_{1011}(x_{10}, x_{11}) = 0.05 \cdot \left(\frac{x_{10} - 1}{5}\right) + 0.15 \cdot \left(\frac{x_{11}}{20}\right) + 0.8 \cdot \left(\frac{x_{10} - 1}{5}\right) \cdot \left(\frac{x_{11}}{20}\right)$$

Step 5: Weight Value Hierarchy

The value hierarchy enables the evaluation framework to be subdivided into many quantifiable factors; however, all are not of equal importance. In a weighted additive value model, the weight factor allows for relative importance to be considered in the composite value score. Of the many methods for assessing weight factors, two were considered, rank based weighting and swing weighting. Rank based weighting can be employed when the SDM has limited availability because it has a less burdensome elicitation process. Swing weighting accurately reflects the SDMs preference structure but requires a more detailed and thus longer data collection process. Local swing weighting, anchored on the most important factor, was employed for this research. This technique compares the subordinate values in a single branch of the hierarchy. The subordinate values are then ranked from most to least important by assessing the order in which the SDM would swing them from the least preferred to most preferred level. The most important value would then be awarded an arbitrary importance score (m). The relative importance of the other values, as a function of m, would then be found using indifference assessments. This is repeated for all levels of all branches. The scores are then normalized such that the weights of the lowest level values sum to one for use in the MAVF. The SDM for this research was technically astute and was subsequently able to provide pre-normalized local swing weights.

Fundamental Objective Weighting: Maximizing the value of an open interface implementation requires consideration of the fundamental objectives based on the relevant sociopolitical environment. The decision maker was asked to determine the weights for the fundamental objectives conditioned on the sociopolitical environment of the MQ-1 and MQ-9 over the past ten years. The SDM's subjective assessment indicated that meeting schedule expectations was preferred to obtaining the lowest cost or meeting acquisition performance expectations.

Table 15: Fundamental Objective Weighting

Value	Local Weight
Minimize Acquisition Cost	0.15
Meet Acquisition Performance Expectations	0.25
Meet Schedule Expectations	0.60

Meet Acquisition Performance Expectations Weighting: The evolutionary nature of technology and the need to maintain a tactical advantage over the adversary drive system changes. Accordingly, the SDM placed the most weight on Adjust to Change because without change an open interface has very little value. Additionally, developing a technological advantage is of little value if it cannot be utilize by the intended users. Therefore the second highest weight was applied to Support Users. Finally, the willingness to share information, inherent to an open interface, conflicts with methods of maintaining a technological advantage by protecting information. The SDM believed while the information protection level inhibited openness it did not preclude it and subsequently placed the lowest weight on Protect Information.

Table 16: Meet Acquisition Performance Expectations Weighting

Value	Local Weight
Adjust to Change	0.45
Protect Information	0.2
Support Users	0.35

Adjust to Change Weighting: The goal of implementing an open interface is to tolerate change, not for the interface itself to induce change. Therefore, the SDM assigned the highest weight to Minimize Interface Change. Adjust to Technology Change and Adjust to Threat Change were both weighted significantly lower. Adjust to Technology Changes was weighted slightly lower because technology changes can drive compatibility issues with an interface. Thus the SDM determined that a high level of technology change does not add as much value to an open interface implementation as a high level threat change.

Table 17: Adjust to Change Weighting

Value	Local Weight
Adjust to Technology Change	0.15
Adjust to Threat Change	0.25
Minimize Interface Change	0.6

Support Users Weighting: The MQ-1 and MQ-9 are multirole aircraft which support both Intelligence, Surveillance, and Reconnaissance (ISR) missions and Air to Ground attach missions. The SDM assessed the highest weight on Support Variety of

Systems. The next most highly weighted value was Support User Community. Finally, the SDM assigned the lowest weight to Support Quantity of Systems because an open interface can still be valuable if there are not multiple functionally equivalent systems that connect.

Table 18: Support Users Weighting

Value	Local Weight
Support User Community	0.3
Support Quantity of Systems	0.1
Support Variety of Systems	0.6

Global Weights

After the local weights were determined the weights for each of the lowest level values were calculated. The value hierarchy including evaluation measures and global weights is shown in Figure 19.

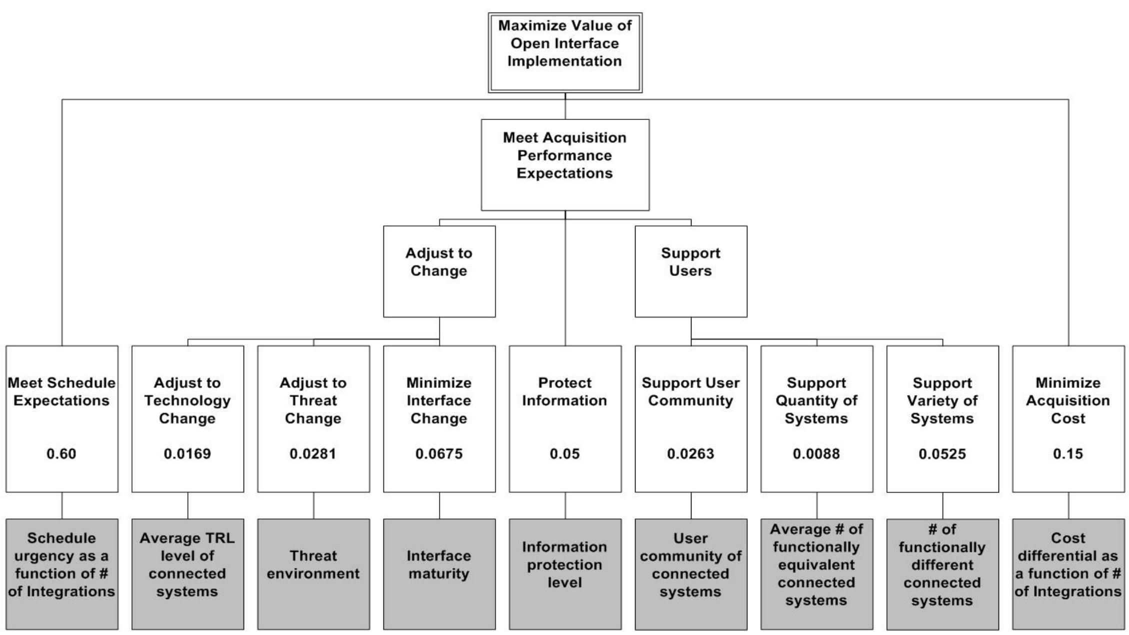


Figure 19: Interface Evaluation Framework Value Hierarchy Including Global Weights

Local Ranks

During the weighting process the SDM was asked to locally rank the hierarchy. These local ranks were used with the rank sum, rank exponent, rank reciprocal and ROC weight determination methods. The value hierarchy including local ranks is shown in Figure 20.

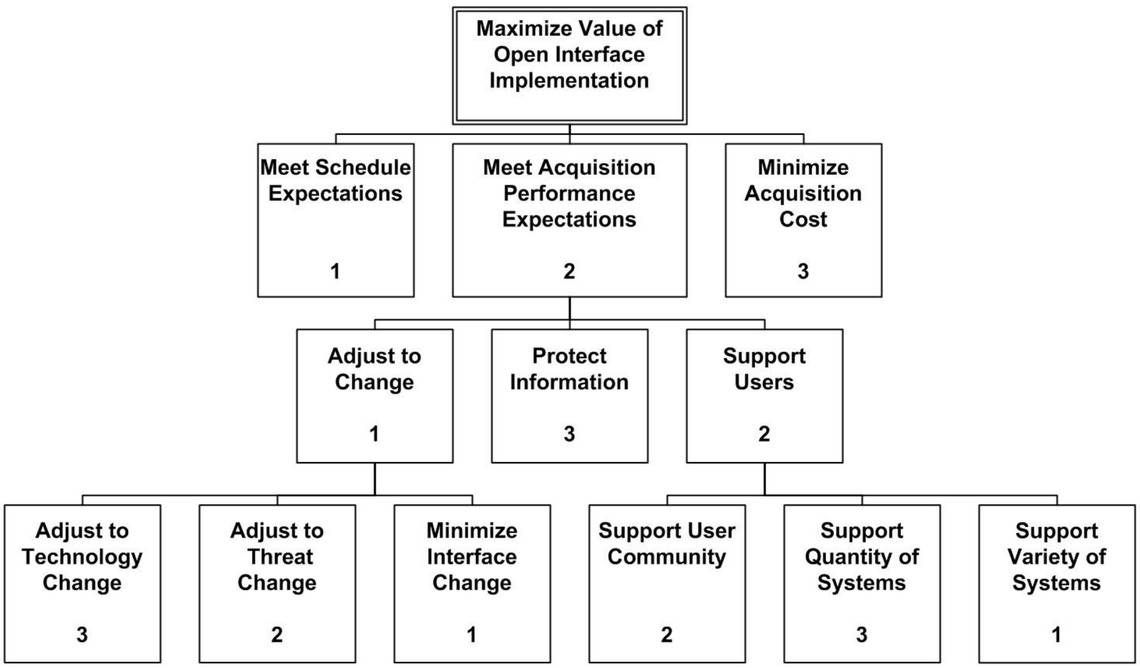


Figure 20: Interface Evaluation Framework Value Hierarchy Local Ranks

Multiattribute Value Function

The structure of the value hierarchy and the lack of preferential independence within the cost and schedule branches dictated a MAVF of the form depicted in equation (18). Equation (18) is an additive value function with multilinear elements that capture

(18)

$$V(X_i) = w_1 \cdot v_1(x_1) + w_2 \cdot v_2(x_2) + w_3 \cdot v_3(x_3) + w_4 \cdot v_4(x_4) + w_5 \cdot v_5(x_5) + w_6 \cdot v_6(x_6) + w_7 \cdot v_7(x_7) + w_{89} \cdot v_{89}(x_8, x_9) + w_{1011} \cdot v_{1011}(x_{10}, x_{11})$$

Where

$X_i = (x_1, x_2, x_3, \ldots x_{11})$

attribute dependence where necessary. Though this function is more complicated than the additive value function, it provides a more accurate representation of the SDM's preferences. After all SAVFs, multilinear value functions, and weight factors were determined the final MAVF, shown in equation (19), was constructed to determine the value of each interface implementation.

(19)

$$V(X_i) = 0.0169 \cdot v_1(x_1) + 0.0281 \cdot v_2(x_2) + 0.0675 \cdot v_3(x_3) + 0.05 \cdot v_4(x_4) + 0.0263 \cdot v_5(x_5) + 0.0088 \cdot v_6(x_6) + 0.0525 \cdot v_7(x_7) + 0.15 \cdot \left(0.0 \cdot v_8(x_8) + 0.05 \cdot v_9(x_9) + 0.95 \cdot v_8(x_8) \cdot v_9(x_9)\right) + 0.60 \cdot \left(0.05 \cdot v_{10}(x_{10}) + 0.15 \cdot v_{11}(x_{11}) + 0.80 \cdot v_{10}(x_{10}) \cdot v_{11}(x_{11})\right)$$

Where

$X_i = (x_1, x_2, x_3, \ldots x_{11})$

$V(X_i)$ = Value of an open interface implementation for scenario X

x_i = Attribute i of scenario X

$v_j(x_i)$ = Component value score for attribute i of scenario X

Hierarchy Quality Evaluation

A subjective quality assessment was conducted based on six factors described in Step 2 of Chapter 2: Completeness, Non-Redundancy, Decomposability, Operability, Conciseness and Input Quality. Each factor was assessed on a scale from 1-4 as described in Table 19. The spider-web diagram, Figure 21, is a graphical representation of the assessment. The rationale used for assessing each factor is described below.

Table 19: Hierarchy Quality Rating Scale

Rating	Description
1	No issues identified with subject factor
2	Minor issues identified with subject factor
3	Major issues identified with subject factor
4	Factor not considered during hierarchy development

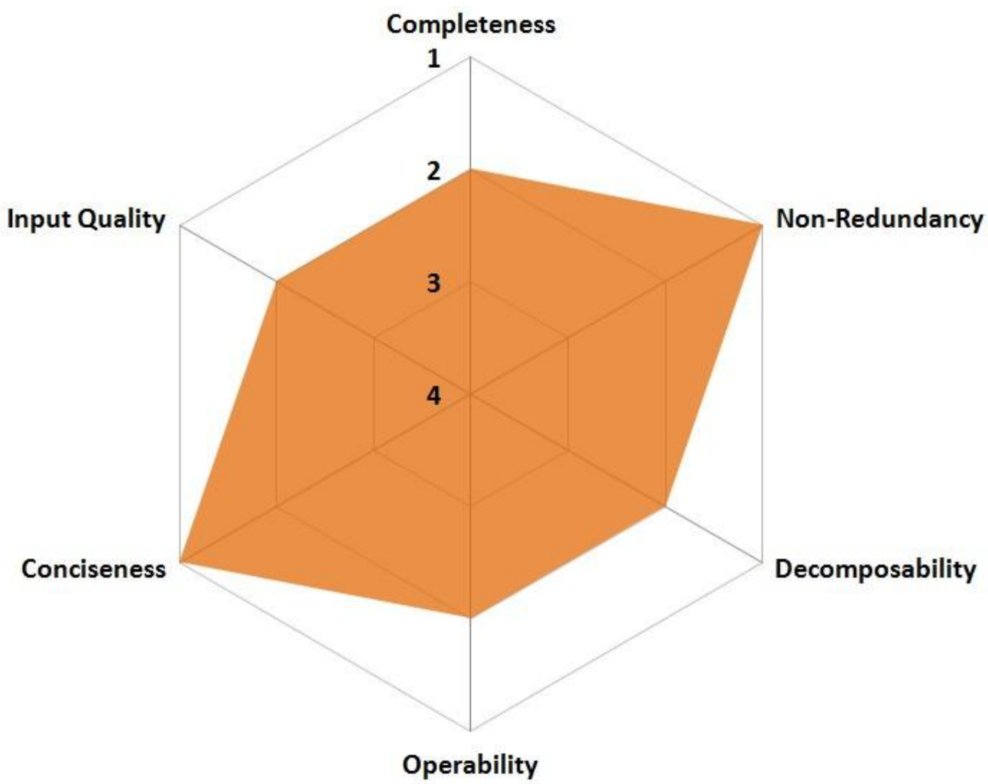


Figure 21: Hierarchy Quality Evaluation

Completeness: The subjective assessment of completeness resulted in a score of two. Multiple resources were consulted from academia, doctrine and personal communication to develop an exhaustive list of evaluation factors. The personal communication element of the investigation focused solely on a UAS system program office. Thus any factors not identified in the academic and doctrinal examination would be specific to medium altitude UAS acquisition.

Non-Redundancy: The value hierarchy was scored a one for non-redundancy. There were ten value measures considered for the value hierarchy that contributed the nine different component values. The number of integrations is used in both the Minimize Acquisition Cost and Meet Schedule Expectations values. The SDM believed that the number of integrations was relevant to both values but it would contribute differently to each therefore this was not considered an issue. Further support for the use of common measures across multiple upper level objectives can be found in the paper by Merrick, Parnell, Barnett, and Garcia describing their analysis of the Upham Brook Watershed (2005).

Decomposability: The subjective assessment resulted in a score of two for decomposability. Two of the nine lowest level values in the final hierarchy employed a multilinear functional form to capture interactions between value measures. This is considered a minor issue because while the hierarchy could not be fully decomposed to independent elements the dependent elements were captured with multilinear functions.

Operability: The value hierarchy was scored two for operability. The intended users of the interface evaluation framework are decision makers within the acquisition community. All values and value measures were selected based on direct input from an IPT and SDM from the acquisition community. During the scoring process it was identified that many of the cost differential estimates were outside the bounds of the scale for this value. The result of this issue is that the framework does not show great sensitivity to cost. Any scenario with cost to implement an open interface that was more than double the cost to implement a closed interface received the same score. Further research would be necessary to determine if the cost scale needs to be adjusted. If an adjustment were necessary, the swing weights would also need to be revisited. This issue was considered minor for operability because the scale was well understood by the scoring official but needs to be refined. All other measures demonstrated good operability.

Conciseness: The conciseness of the hierarchy was assessed a score of one. The lowest level values did not indicate any conceptual overlap.

Input Quality: The hierarchy development leveraged silver and gold inputs to develop an initial draft. Platinum inputs were leveraged to aggregate and refine the draft hierarchy to arrive at the final product. The extensive use of SDM inputs provides for strong input quality; however the breadth of input was limited to a single platform type and mission area. The input quality was scored a two because of the limited breadth of platinum standard inputs.

Summary

Chapter 3 provided a detailed overview of the methodology that was utilized to collect and analyze data in support of the research objectives. The first step in the VFT process, problem definition, was discussed. The chapter then outlined the data required, method of collection and method of analysis for the following VFT process steps: Create Value Hierarchy (Step 2), Develop Evaluation Measures (Step 3), Create Value Functions (Step 4), Weight Value Hierarchy (Step 5). Alternative Generation, Alternative Scoring, Deterministic Analysis and Sensitivity Analysis (Steps 6-9) will be discussed in Chapter 4. The final step, Conclusions and Recommendations (Step 10) is addressed in Chapter 5.

IV. Analysis and Results

Chapter Overview

This chapter discusses the results obtained from the application of the interface evaluation framework to historical interface decision scenarios, and the associated sensitivity analysis. Alternatives were selected to capture a cross section of interface decisions made on the MQ-9 program. Subject matter expert inputs were used to obtain value scores on fifteen alternatives, interface scenarios, from the early stages of the MQ-1/MQ-9 UAS programs. The chapter begins with a discussion of the alternatives. This is followed by a description of the scoring procedure and an examination of the resulting scores, relevant assumptions, and observations. Next, the implications of the value scores are explained. Finally, the results of the sensitivity analysis, areas of sensitivity, and a comparison of decision factors are described.

Step 6: Alternative Identification

The evaluation framework was developed with the goal of identifying interfaces that would benefit from the from open interface implementation. Therefore an interface scenario that receives a high score would be a good candidate for the use of open IIMs. Conversely, an interface scenario that receives a low score would be a good candidate for the use of closed IIMs. This research divides the choices available to the SDM for any interface scenario into four categories of action taken which correlate with the four model recommendation categories: *implemented open*, *implemented closed*, *invested in open*, and *considered open*. The goal of interface scenario selection was to capture a cross section of different categories using a subset of the interfaces that exist on the MQ-9 platform. The resulting sample data included a set of fifteen interface implementation scenarios. The ***implemented open*** category, where the a program office chose to implement the most mature standard that existed, proved to be uncommon which resulted in only two identified scenarios. It was suspected that this is related to the cutting edge nature of military systems. By the time an interface has reached full maturity there are less mature higher performance interfaces available. The ***implemented closed*** category, where the program office chose to implement an IML 1 or IML 2 interface standard, was not intuitive and resulted in only two identified scenarios. The ***invested in open*** category, where the program office chose to invest resources to document or mature a closed interface, were very common which resulted in ten identified scenarios. Finally, the ***considered open*** category, where a mature standard existed yet the program office chose to implement a less mature interface, were infrequent and resulted in only one scenario. Due to the nature of the military capabilities involved with these fifteen interfaces, all scenarios will be referred to by an interface number and a designation as either electrical (E) or mechanical (M). A description of the 15 interface scenarios is provided in Table 20.

Table 20: Interface Scenario Descriptions

Interface Scenario	Description
1M	Communications Mechanical Interface
1E	Communications Electrical Interface
2M	Mission System Mechanical Interface
2E	Mission System Electrical Interface
3M	Mission System Mechanical Interface
3E	Mission System Electrical Interface
4M	Safety System Mechanical Interface
4E	Safety System Avionics Electrical Interface

5M	Data Transmission System Mechanical Interface
5E	Data Transmission System Electrical Interface
6M	Mission System Mechanical Interface
6E	Mission System Electrical Interface
7E	Ground Station Peripheral Electrical Interface
8E	Mission System Electrical Interface
9E	Avionics Electrical Interface

Step 7: Alternative Scoring

Scoring Procedure

The scoring procedure involved examination of each historical interface scenario against the value measures captured in the model. A high level systems engineer from the Medium Altitude UAS System Program Office was chosen to perform the assessment because he possessed both access to the necessary information and experience, within the program office, with all aspects of model. The scoring official was provided an Excel-based evaluation tool, which provided scales, descriptions, and sliding scales for each measure. The inputs to the model captured the actual occurrences covering approximately a ten year period leading up to the research period. The scoring official was asked to provide his best assessment for each measure. Estimates were utilized where necessary to work within the time constraints of the research.

Step 8: Deterministic Analysis

The weighted value scores obtained from the historical interface scenario assessment conducted by the scoring official are shown in Table 21. The maximum value interface scenario shown on the top line of the left column represents an interface scenario in which the maximum score was achieved in all value measures. Additionally,

Table 21: Weighted Value Scores

Interface Scenario	Weighted Value Score $(V(X_i))$	Interface Scenario	Weighted Value Score $(V(X_i))$
Maximum Value	1.000	4 M	0.0984
8 E	0.4049	4 E	0.0984
6 M	0.2820	1 M	0.0855
6 E	0.2535	1 E	0.0855
7 E	0.2277	2 M	0.0843
9 E	0.1320	2 E	0.0843
5 M	0.1199	3 M	0.0809
5 E	0.1199	3 E	0.0809

Figure 22 provides a graphical depiction of the contribution of each of the component values to the weighted value score for each of the historical scenarios. Each interface scenarios is represented by an interface number followed by an E, for electrical component, or M, for mechanical component of the interface. While none of the interface scenarios scored particularly high, the value scores indicate that the electrical

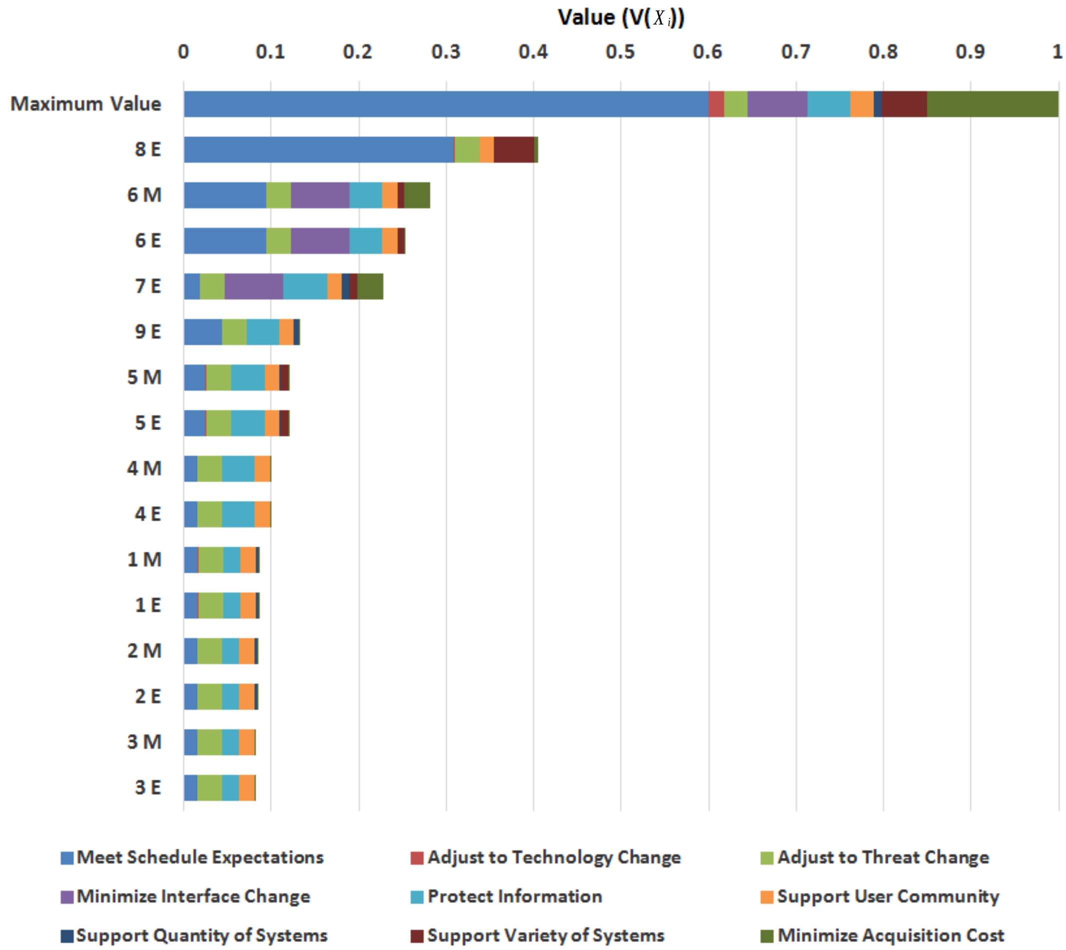


Figure 22: Open Interface Implementation Value Breakout

component of interface scenario eight (8E) held the most value for an open interface implementation. Relevant assumptions and observations for each of the value measures are described in the following sub-sections.

Scoring Assumptions and Observations

The IEF was developed to aid SDMs with interface decisions based on a ten year planning horizon. This means that if the IEF were used as intended, the scoring official would be providing scores based on what he/she believed would occur over the ten years following the decision. The assumptions and observations captured below are based on a historical data set. Subsequently, the data captures what occurred over the past ten years.

Number of Functionally Different Connected Systems: For this value measure the scoring official counted the number of functionally different systems that were connected to the interface over the past ten years. To assess this and several other scores the scoring official must delineate between the host, the system that is being connected to, and the tenant(s), the system(s) that are connected to the host. The term *connected systems* is referring to the tenant system(s) as determined by the scoring official. Two connected systems were considered *functionally different* if they connected at the interface, yet the requirements for the systems were different. For example, if the SDM expected to connect a printer and a scanner to the same interface, a score of two would be obtained. This is because the technical requirements met by the printer would clearly be different than those met by the scanner. Interface scenario 8E, 6E, and 6M obtained a score of twelve, four, four respectively. All of the other interface scenarios scored either a one or two on this measure, while the maximum possible score was a twenty. This result was not unexpected. The attribute scale needs to capture the majority of possible outcomes; however, interfaces that support many functionally different systems are not as prevalent as those that support one or two.

Average Number of Functionally Equivalent Connected Systems: The scoring official calculated the average number of functionally equivalent systems that were connected to the interface over the past ten years. Two connected systems were considered functionally equivalent if both systems met or exceeded the same set of performance requirements. Knowledge of the number of functionally different connected systems was required prior to scoring this measure. From the example above, if five different printers were available to meet the printer technical requirements and three different scanners were available to meet the scanner technical requirements then a score of four would be obtained.

It was expected and confirmed through scoring that all of the interface scenarios scored low in this measure. Systems exist that have many comparable, functionally equivalent, replacements. However, it is suspected that these systems do not often dovetail with the very specific, high performance requirements of a long endurance, medium altitude UAS.

Average TRL of Connected Systems: This value measure required the scoring official to subjectively assess the Technology Readiness Level of the systems connected at the interface. The TRL for each of the connected systems were then averaged to obtain a score.

Threat Environment: For this value measure the scoring official made a subjective determination of the threat environment that would be impacting development over the past ten years. Because all historical interface scenarios were coming from the same time period it was expected that a common score would be obtained for all fifteen interface scenarios.

Interface Maturity: The scoring official examined the interfaces standards available for implementation at the time of decision. The maximum maturity level of the available interface standards dictated the value score. Twelve of the fifteen interface scenarios indicated that the maturity of the interface standards available at the time of the decision were level 1, where no defined standard existed and changes were controlled by the integrator. The interface standards available for the remaining three scenarios were documented and controlled by the Department of Defense or a commercial standards agency and thus were assessed as a level 4 IML.

Information Protection Level: For this value measure the scoring official assessed the highest IPL of the connected systems. All but one of the scenarios under consideration were assessed as having a maximum IPL of either Secret or Unclassified FOUO. The remaining scenario, 8E, had a maximum IPL of Compartmentalized Top Secret.

User Community of Connected Systems: This value measure required the scoring official to examine the user community of the connected systems. The value score captured the user community for all connected systems. If all of the users of the connected systems came from the same unit then a value score of one would be awarded. If the users came from different units but all within the USAF then a value score of three would be awarded. All of the historical scenarios under consideration came from the MQ-9 UAS Air Vehicle. The MQ-9 is a Foreign Military Sales (FMS) asset that is shared with other countries. Because of the FMS status of the Air Vehicle all scenarios were scored a level 5 for this value measure.

Number of Integrations at the Interface: For assessing historical data, the scoring official looked at the number of integrations that were performed at the interface over the past ten years. If using the evaluation framework to examine a current decision the scoring official would assess the number integrations based on planned upgrades, evolutions, and/or system integrations.

Cost Differential: This value measure required the scoring official to determine the cost to implement a closed interface and the cost to implement an interface with the highest interface maturity available. The two costs were used to calculate the ratio of cost difference to the cost to implement a closed interface. This ratio provided the value score. If the highest IML available was a level 1 or level 2 then the cost to obtain a government owned ICD would be used. In all of the historical scenarios detailed cost data was unavailable. A subject matter expert estimate was used in lieu of detailed cost data. For future evaluations it is likely that detailed cost information would be available for assessment of this value score. For twelve of the fifteen scenarios the scoring official determined that the cost to obtain a government owned ICD was more than double the cost of implementing a closed interface. In scenario 6E the scoring official indicated that the cost of additional hardware required to support implementing an IML 4 interface was more than double the cost of implementing a closed interface. The scale for cost differential did not account for costs of this magnitude and thus the maximum score of one was awarded for all scenarios indicating a component value score of zero. The remaining two scenarios in which an IML 4 was available, the scoring official indicated that the cost differential was zero indicating a component value score of one.

Schedule Urgency: This value measure required the scoring official to examine the schedule urgency of integrations over the past ten years based in mission priority. Because each of the integrations could have a different mission priority, the scoring official was asked to provide an overall assessment of the mission priority of integrations at the interface. Though there are many users of the MQ-1 and MQ-9 UASs, many system changes, whether driven by technology change or threat change, are filtered through a single unit which prioritizes modifications and provides direction for the program office. This prioritization resulted in eleven of the fifteen scenarios being scored a Level 2 for schedule urgency.

Implications of the Value Score

The IEF allows the SDM to systematically obtain a value score for an interface. The question remains, "How does one use the value score information to make a decision about interface implementation?" Figure 23 provides a means of interpreting the value scores by comparing them to the IML of available interface standards. The threshold

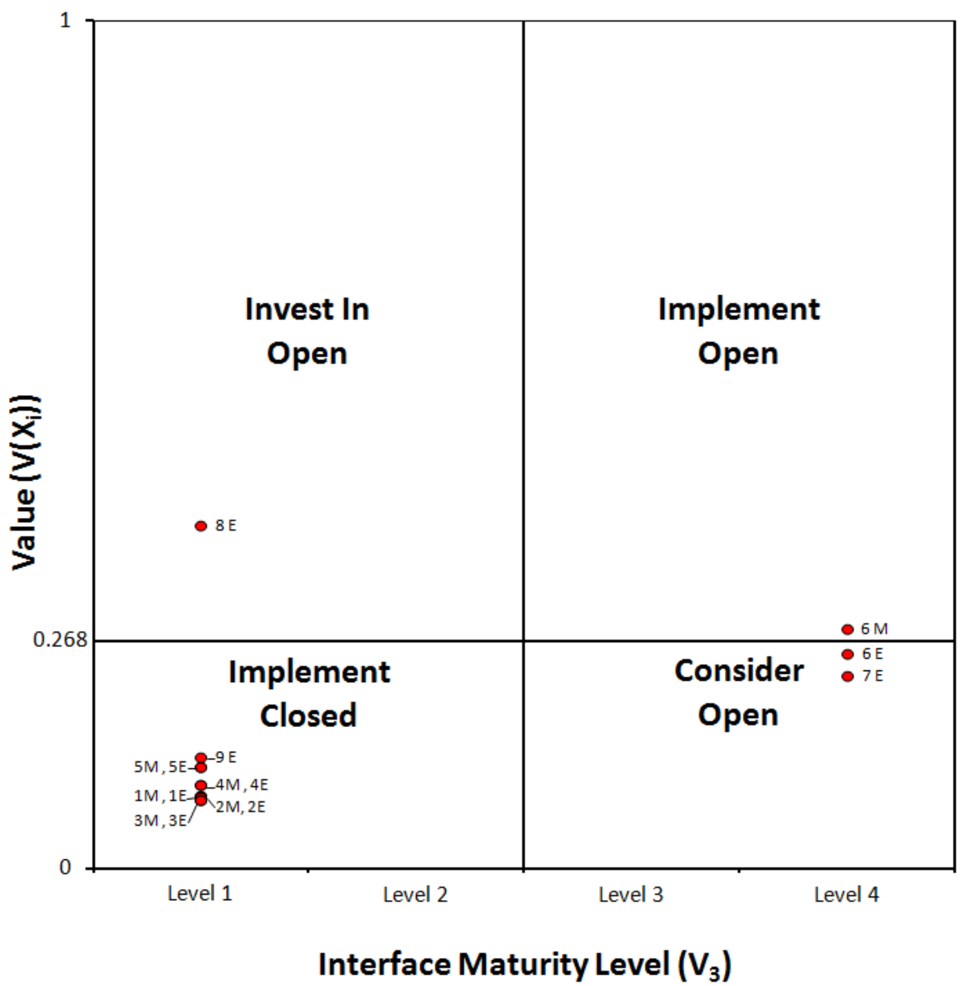


Figure 23: Value Score Interpretation

value score is set to 0.268 based on historical decision data. The ***Implement Closed*** quadrant is associated with scenarios that obtain little value for the implementation of an open interface and available interface standards are at an IML 1 or 2. In other words, there is not a business case for an open interface and the standards are immature. The ***Implement Open*** quadrant is associated with scenarios that obtain high value for an open interface and interface standards that are at an IML 3 or 4. This indicates that there is a strong business case for an open interface and documented, controlled interface standards are available. The ***Invest In Open*** quadrant is associated with scenarios that obtain a high value for the implementation of an open interface but documented, controlled interfaces are not available. This situation would suggest to the SDM that investment in developing or maturing the interface standard may be a worthwhile endeavor. Finally, the ***Consider Open*** quadrant is associated with scenarios that obtain low value for an open interface but IML 3 or 4 standards are available. This situation would suggest that use of an open interface is preferred if no additional resources, time or money, are required. This graphic is only meant to provide guidance to the decision maker. The value scores and IML levels of the historical interface scenarios are indicated by red circles in Figure 23. Table 22 provides an examination of the model recommendation, actual implementation decision, and subjective commentary on discrepancies for each of the historical scenarios.

Table 22: Model Recommendation Vs. Actual Action Taken

Interface Scenario	Model Recommendation*	Action Taken	Comments/Rationale
1 M	Implement Closed	Invested in Open at IML 3	The Program Office invested in ICDs based on major system interfaces. Guiding documents do not provide explicit methods or metrics for business case analysis of key interfaces (IPT Engineering, personal communication, January 16, 2014).
1 E	Implement Closed	Invested in Open at IML 3	
2 M	Implement Closed	Invested in Open at IML 3	
2 E	Implement Closed	Invested in Open at IML 3	
3 M	Implement Closed	Invested in Open at IML 3	
3 E	Implement Closed	Invested in Open at IML 3	
4 M	Implement Closed	Invested in Open at IML 3	
4 E	Implement Closed	Invested in Open at IML 3	
5 M	Implement Closed	Invested in Open at IML 3	
5 E	Implement Closed	Invested in Open at IML 3	
6 M	Implement Open	Implemented Open at IML 4	No Discrepancy
6 E	Consider Open	Considered Open at IML 4 but implemented IML 3	An IML 4 MIL-STD existed however the cost to implement fully was prohibitive. The choice was made to implement a tailored version of the MIL-STD. The implementation of an IML 3 interface is in line with the model recommendation (IPT Engineering, personal communication, January 16, 2014).
7 E	Consider Open	Implemented Open at IML 4	An IML 4 commercial standard existed and was implemented at no added cost (IPT Engineering, personal communication, January 16, 2014). The implementation of an IML 4 interface is in line with the model recommendation.
8 E	Invest In Open	Implemented Closed at IML 1	The Program Office is currently investigating the implementation of an IML 3 interface. Information available at the time of program planning did not indicate a need for an open interface. However, numerous integrations were added to the program plan to meet various mission needs (IPT Engineering, personal communication, January 16, 2014).
9 E	Implement Closed	Implemented Closed at IML 1	No Discrepancy
*Model recommendation is based on a Threshold Value Score of 0.268			

Step 9: Sensitivity Analysis

The goal of sensitivity analysis is to examine the impact of input changes on the output and recommendations of the model. The various sensitivity analyses conducted on the IEF are described below. First, a weighting technique comparison was conducted to examine the effect of different weighting techniques on the model output. Following the weighting technique comparison a rank order sensitivity analysis explored the impact of weight variations on the rank order of alternatives. Next, a value threshold sensitivity analysis captured the areas of sensitivity to an established threshold associated with a open/closed implementation decision point. Finally, an exploration of the impact of changing the bounds on the number of integrations value measure on the decision threshold was conducted.

Weight comparison

Swing weighting, an indirect weighting technique, was used to establish the weights for the evaluation framework multiattribute value function (MAVF). However, several other direct weighting techniques using swing ranks were considered. Table 23 shows a comparison of the swing weights to the weights that would have been obtained if the local swing ranks were utilized with each of the direct techniques to calculate global weights. The table shows great consistency between the various techniques. Though the table shows consistency, in many cases it only takes small variations in the weights to effect the rank order of alternatives. Table 24 shows the rank order that would have been indicated with each of the different weighting techniques. The rank order remains generally consistent across all of the weighting techniques. The only area of inconsistency is highlighted in grey. The Rank Sum indicated an order change between scenario 6E and scenario 7E.

Table 23: Weight Variations by Technique

Value	Weighting Technique				
	Swing Weight	Rank Sum	Rank Exponent	Rank Reciprocal	Rank Order Centroid
Meet Schedule Expectations	0.600	0.500	0.600	0.545	0.611
Adjust to Technology Change	0.017	0.028	0.017	0.027	0.019
Adjust to Threat Change	0.028	0.056	0.056	0.041	0.047
Minimize Interface Change	0.068	0.083	0.110	0.081	0.104
Protect Information	0.050	0.056	0.029	0.050	0.031
Support User Community	0.026	0.037	0.028	0.020	0.021
Support Quantity of Systems	0.009	0.019	0.009	0.014	0.009
Support Variety of Systems	0.053	0.056	0.056	0.041	0.047
Minimize Acquisition Cost	0.150	0.167	0.096	0.182	0.111

Table 24: Alternative Ranks According to Weighting Technique

Rank	Weighting Technique				
	Swing Weight	Rank Sum	Rank Exponent	Rank Reciprocal	Rank Order Centroid
1	8 E	8 E	8 E	8 E	8 E
2	6 M	6 M	6 M	6 M	6 M
3	6 E	7 E	6 E	6 E	6 E
4	7 E	6 E	7 E	7 E	7 E
5	9 E	9 E	9 E	9 E	9 E
6	5 M	5 M	5 M	5 M	5 M
7	5 E	5 E	5 E	5 E	5 E
8	4 M	4 M	4 M	4 M	4 M
9	4 E	4 E	4 E	4 E	4 E
10	1 M	1 M	1 M	1 M	1 M
11	1 E	1 E	1 E	1 E	1 E
12	2 M	2 M	2 M	2 M	2 M
13	2 E	2 E	2 E	2 E	2 E
14	3 M	3 M	3 M	3 M	3 M
15	3 E	3 E	3 E	3 E	3 E

Rank Sensitivity

The robustness of the model was examined through a single factor sensitivity analysis. The goal of this analysis was to explore the impact of changes in weight factors on the rank order and overall value score of alternatives. A summary of the results of the analysis is provided in this section. The full results, in graphical form, can be found in Appendix B: Sensitivity Analysis. Each graph is an examination of a single weight factor. The red vertical line indicates the weight determined by swing weighting. The x-axis represents the weight factor, varying from zero to one, and the y-axis indicates the weighted value score, varying from zero to one. Each of the fifteen historical interfaces scenarios are shown in a different color. The intersection of the red vertical line and interface scenario line illustrates the weighted value score obtained under the assessed swing weights described in Chapter 3. Moving to the left (right) of the red line indicates the effect of a decrease (increase) in weight on the value score.

It was expected that, due to the variation in component value scores of many of the historical interface scenarios, the evaluation framework would exhibit sensitivity to changes in weight for many of the values. The values that showed sensitivity to weight changes were, Meet Schedule Expectations, Minimize Interface Change, Protect Information, Support Quantity of Systems, and Minimize Acquisition Cost. As can be seen in Figure 24 scenario 8E holds the highest value score at the elicited weights. However, if the weight (0.0675) applied to Minimize Interface Change were increased to >0.18, while all others were proportionally adjusted, the highest valued alternative would change to scenario 6M.

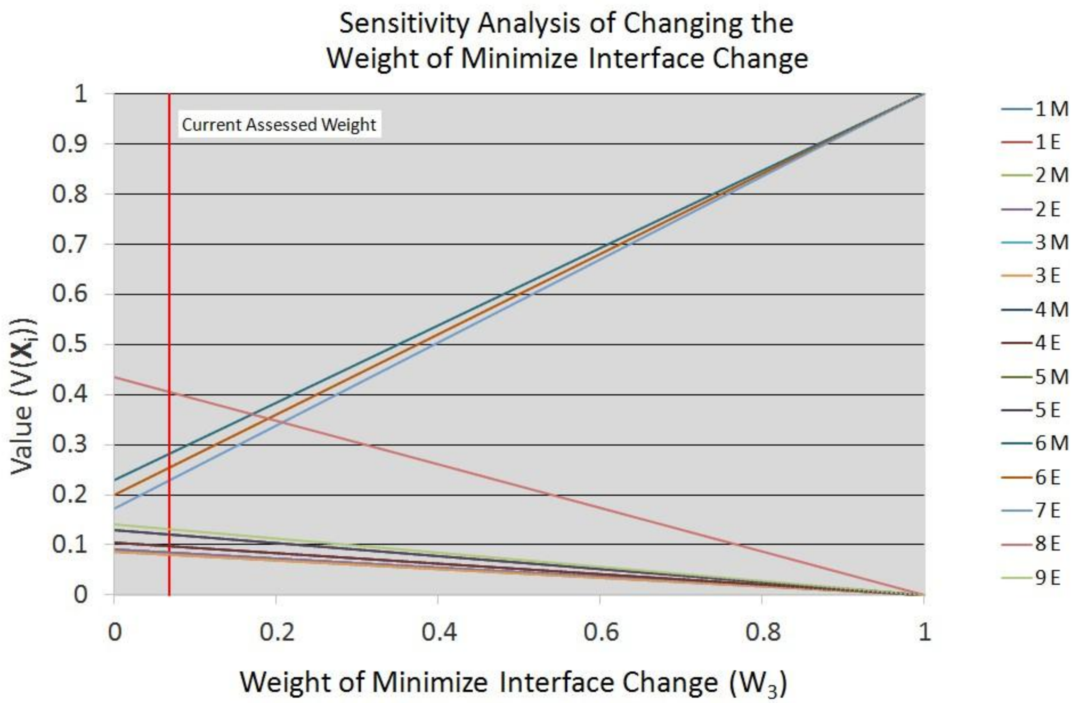


Figure 24: Sensitivity Analysis of Changing the Weight Applied to the Minimize Interface Change Value

Value Threshold Sensitivity

The scenario value score as it relates to the threshold value score is the primary focus of the evaluation framework because it provides the SDM direction on which interfaces should employ an open interface and which should not. Above this threshold the SDM should choose to employ open interface standards if possible. Conversely, below this threshold the SDM should choose to employ a closed interface. This sensitivity analysis examines the impact of adjustments to the weights that would cause a particular alternative to rise above or fall below the threshold of interest. The threshold value score, indicated by a horizontal red line, was added to the graph described in the previous section. Figure 25 shows an example using a threshold value score of 0.268.

Figure 26 shows a magnified view of the black outlined section of Figure 25. As can be seen in Figure 26, at the current assessed weight only two interface scenarios had value scores that rose above the threshold value score. This indicated that, of the scenarios

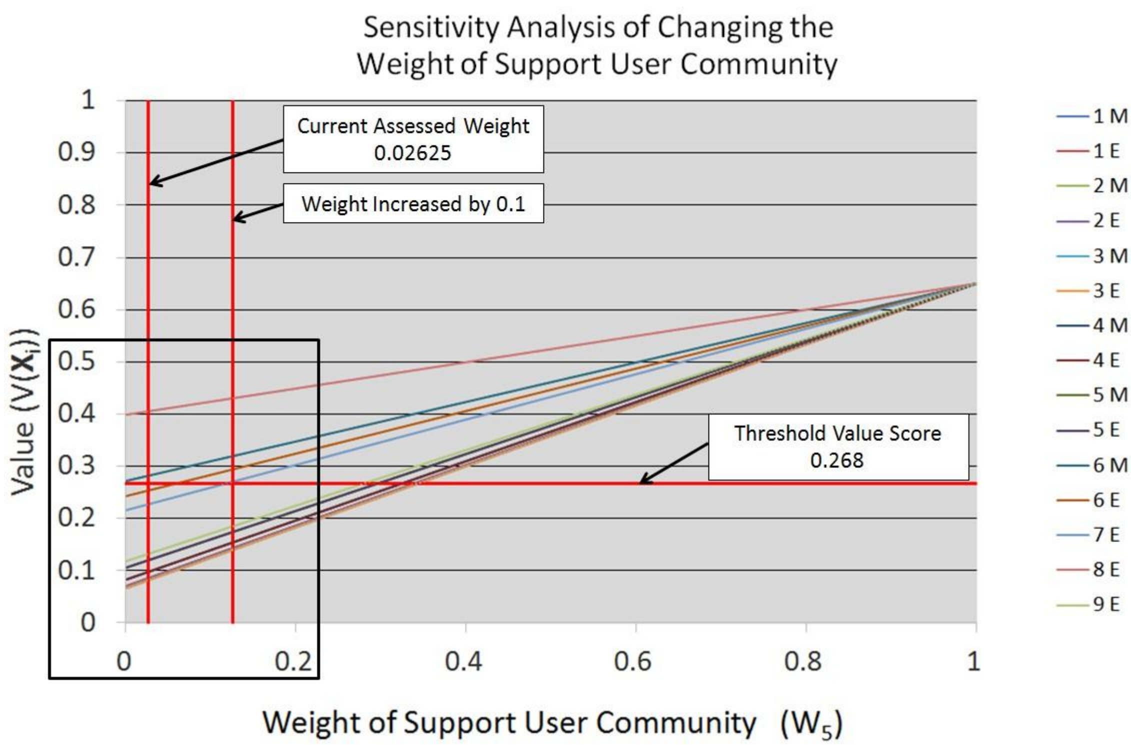


Figure 25: Example Value Score Sensitivity

under consideration, only 8E and 6M should employ open interfaces. However, if the weight applied to the Support User Community value were raised to 0.12625 from 0.02625, the model showed that four scenarios were above the representative threshold value score. When sensitivities of this nature are present the SDM is advised to closely examine the subject weights before final decisions are made.

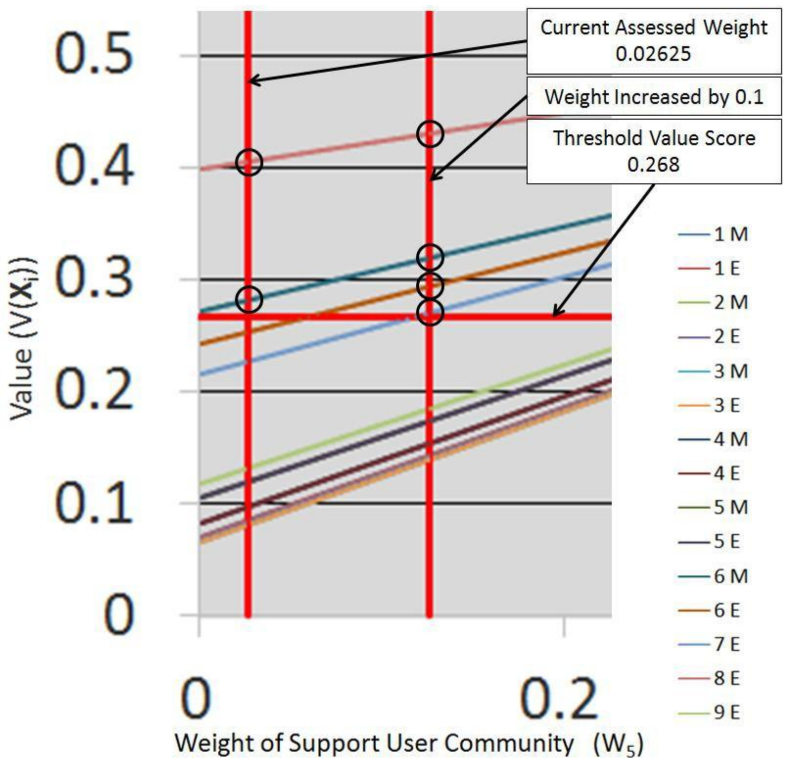


Figure 26: Exploded View of Figure 25

This research attempted to identify a threshold value score for open interface decisions based on very limited historical information. Therefore the value threshold sensitivity analysis was conducted with a score of 0.268. A brief overview of the findings is provided, while the full analysis, in graphical form, is provided in Appendix B: Sensitivity Analysis. It was expected that many of the attributes would exhibit value threshold sensitivity because there was only a small difference between the highest and lowest value score. The analysis showed that a <10% change to the weights applied to six of the nine attributes would result in scenario 6E rising above the value threshold. The attributes that were not included were, Adjust to Technology Change, Support Quantity of Systems, and Support Variety of Systems. Similarly, scenario 7E would rise above the value threshold if a <10% change occurred to the weights of all attributes except Adjust to Technology Change, Support Variety of Systems, and Minimize Acquisition Cost. If weight changes of this magnitude were to occur the model recommendation for both 6E and 7E would change from *Consider Open* to *Implement Open*.

Decision Factor Comparison

The interface decision factors identified by the OSJTF and those uncovered by this research do not match exactly, however many of the same concepts are captured. Conceptual linkages were established to connect the interface decision factors identified by the OSJTF and those decision factors identified through this research. Figure 27 depicts the OSJTF decision factors, from Table 1, in grey rounded rectangles and the IEF decision factors, from Figure 8, in orange rectangles. The lines connecting the factors represent a conceptual overlap between factors as determined by a subjective assessment. The linkages to OSJTF factor 8 are examined as an example. Figure 27 shows that the IEF decision factors, Information Protection, User Community, and Variety of Systems are conceptually linked to OSJTF factor 8. An obvious linkage is that between the information protection factor from the IEF and the need for interface control highlighted by the OSJTF. A less obvious link is between the user community factor and the need for interface control. This linkage captures the fact that as the user community of an interface becomes larger and more varied the need for interface control also, logically, increases. This establishes a conceptual link between the two factors. Further, there is a link between the need for flexibility and modularity and the variety of systems that are, or

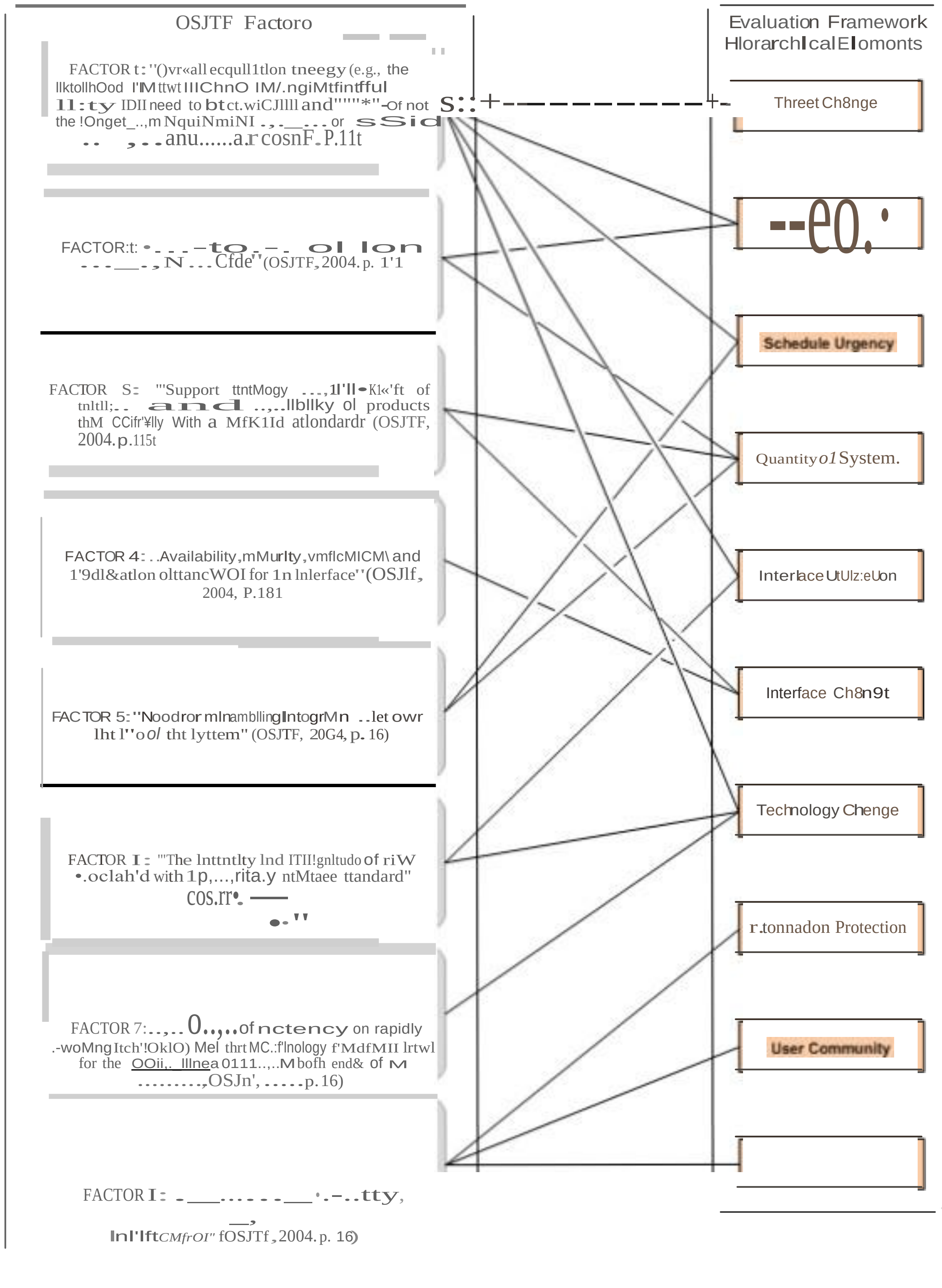

OSJTF Factoro
Evaluation Framework
Threet Ch8nge
Schedule Urgency
Quantity o1 System.
Interface Ch8n9t
Technology Chenge
r.tonnadon Protection
User Community
FACTOR 4: . .Availability, mMurlty, vmflcMICM\ and 1'9dl&atlon olttancWOI for 1n lnlerface''(OSJlf, 2004, P.181

Figure27: Decision Factor Comparison

are intended to be, employed at an interface. If there is a plan to have high number of functionally different systems connected to the same interface, there is an apparent need for a flexibly interface in a modular architecture.

Summary

Chapter 4 provided a synopsis of the results that were obtained and the analysis that was conducted as part of the IEF research. Alternative Generation (Step 6) and Alternative Scoring (Step 7) were discussed first followed by Deterministic Analysis (Step 8) and an explanation of the implications of the value score. The chapter concluded with a series of sensitivity analyses and a comparison of the OSJTF decision factors with those found during the IEF research.

V. Conclusions and Recommendations

The purpose of this research was to develop an evaluation framework and decision support tool to assess the value of an open interface in line with the principles identified in the OSA/MOSA guidance. The initial concentration of the effort was to capture the deterministic factors, evaluation measures for those factors, and the relative importance of each factor to the value of an open interface to construct a multiattribute value function (MAVF). After the MAVF was constructed, based on Silver, Gold, and Platinum inputs, the hierarchy was reviewed for quality. Finally, historical interface scenarios were examined using the evaluation framework.

This chapter begins with an explanation of the significance of the research. Following the significance section, recommendations for the acquisition community to aid in adoption of the IEF and recommendations for future research are provided. Finally, conclusions found during the course of this research are described.

Significance of Research

Current DoD guidance prescribes the use of the MOSA to promote OSA. The OSJTF identifies five principles to guide the acquisition community in the execution of the approach. The guidance provides a broad set of factors to consider when determining which interfaces warrant the application of open standards. However, these factors lack defined metrics and do not indicate the relative importance of the factors. In addition, there does not exist a structured method, process or tool to support interface decisions for MOSA. This research attempted to formalize the OSJTF's broad guidance through the development of a deterministic decision model. A decision model of this nature provides a method for justified and consistent decision making in this area. Further, the use of a decision model provides leadership the ability to decentralize interface decision making while maintaining the ability to control and refine the process.

Recommendations for Action

Initiate data collection for IEF refinement

The model created in this research is a proof of concept that leverages decision analysis tools to structure the values of the acquisition community with respect to open interface implementation. The IEF represents a large set of decision factor inputs; however, the inputs for evaluation measures, swing weights, and historical scenarios were limited to a single program office. It is recommended that leadership in the acquisition community implement a data collection requirement in the program offices based on the evaluation measures defined in this IEF. This data will serve many purposes. First, it will help leadership to better understand the bounds of the value measures and would allow for value measure refinement. Additionally, the information collected will provide a means to refine the threshold value score and facilitate adoption of an evaluation tool of this pedigree in the future.

Examine linearity assumption for interaction terms

The second recommendation for action is to further examine the linearity assumption found in the IEF interaction terms. To simplify the, already arduous, elicitation process, linear functions were assumed for all multilinear component value functions. The author believes that a concave or convex functional form may be more representative of the SDMs value preferences, but was not explored due to the linearity assumption. The SDM was able to solidify his/her relative preferences based on the linear assumption; however, it is possible that some rank inconsistencies exist. Regardless, further examination of this area would provide increased confidence in the results of the framework even if the linearity assumption remains unchanged.

Recommendations for Future Research

Examination of misaligned recommendations

Ten of the fifteen historical scenarios that were examined show a misalignment between the model recommendations and the program office decision. There are two potential explanations for this misalignment. 1) The original analysis conducted by the program office included factors not considered in the IEF. 2) The program office decisions were based on what they believed would occur while the IEF recommendation is based on what actually occurred. The question remains, "Does acquisition leadership believe that the interface implementation decisions that were made on the ten misaligned scenarios were "good" decisions, given what has occurred? If the answer to this question is yes, then additional research is warranted to identify the factors, and associated structure and weights, not considered in the IEF that would resolve the misalignment. If the answer to this question is no then no additional research in this area is necessary.

Application of the IEF value hierarchy to other acquisition portfolios

The Air Force Life Cycle Management Center (AFLCMC) is the organization responsible for weapon system acquisition in the USAF. The organization is divided into many weapon system portfolios, each led by a Program Executive Officer. Some of the major weapon system portfolios are: 1) Intelligence, Surveillance and Reconnaissance /

Special Operations Forces, 2) Tankers, 3) Fighter/Bomber, and 4) Mobility (Air Force Acquisition - Organizations). The value hierarchy, developed as part of the IEF, leveraged inputs from academic research, doctrinal documentation, and subject matter experts from the Medium Altitude UAS program office, part of the ISR/SOF portfolio. Additionally, the evaluation measures utilized in the IEF were also developed purely on inputs from the program office. While the results of the research indicate that the value hierarchy corresponds with those values identified by the OSJTF, which provides MOSA guidance for weapon systems, additional research to confirm the applicability of the IEF to PEO portfolios other than ISR/SOF is needed.

Effect of acquisition portfolio on swing weights and value threshold

In addition to research into the applicability of the hierarchy to other PEO portfolios it is also important to explore the effect, if any, a change in acquisition portfolio would have on the swing weights and value threshold. The swing weights and swing ranks determined for the IEF were based on a single decision frame. A frame which involved a platform in the ISR/SOF portfolio developed during a period of war in which rapidly changing tactics were employed. The SDM indicated that the swing weights applied to the framework represented priorities that were specific to the timeframe and the platform under consideration. Further, the SDM indicated that if the framework were applied to next the ten years rather than the past ten years the weight applied to the cost and performance fundamental objectives would be significantly higher than currently assessed. Additional research into weighting methods that can accommodate for changing portfolios and/or changing acquisition priorities is desirable.

As described in the recommendations for action section above, analysis of more would increase confidence in the value threshold. During model development, two hypotheses could not be confirmed with the available data. First, the value threshold may not be a single level, instead it could be four different levels, each dependent on the IML of the standards available for implementation. The value score interpretation shown in Figure 23 could then be transformed to that depicted in Figure 28. The second hypothesis was that the value threshold/s would be common across all acquisition portfolios. To confirm this hypothesis, data from other weapon system portfolios must be collected and analyzed.

To explore the impact of different acquisition portfolios on both swing weights and value threshold it is recommended that a more expansive data collection effort is undertaken. This effort should include assessment of historical interface scenarios and swing weights from weapon systems in each of the major portfolios covering multiple threat environments. Additionally, qualitative data should be collected to capture any decision influences, such as policy, economic, or political pressures present at the time of the historical decision.

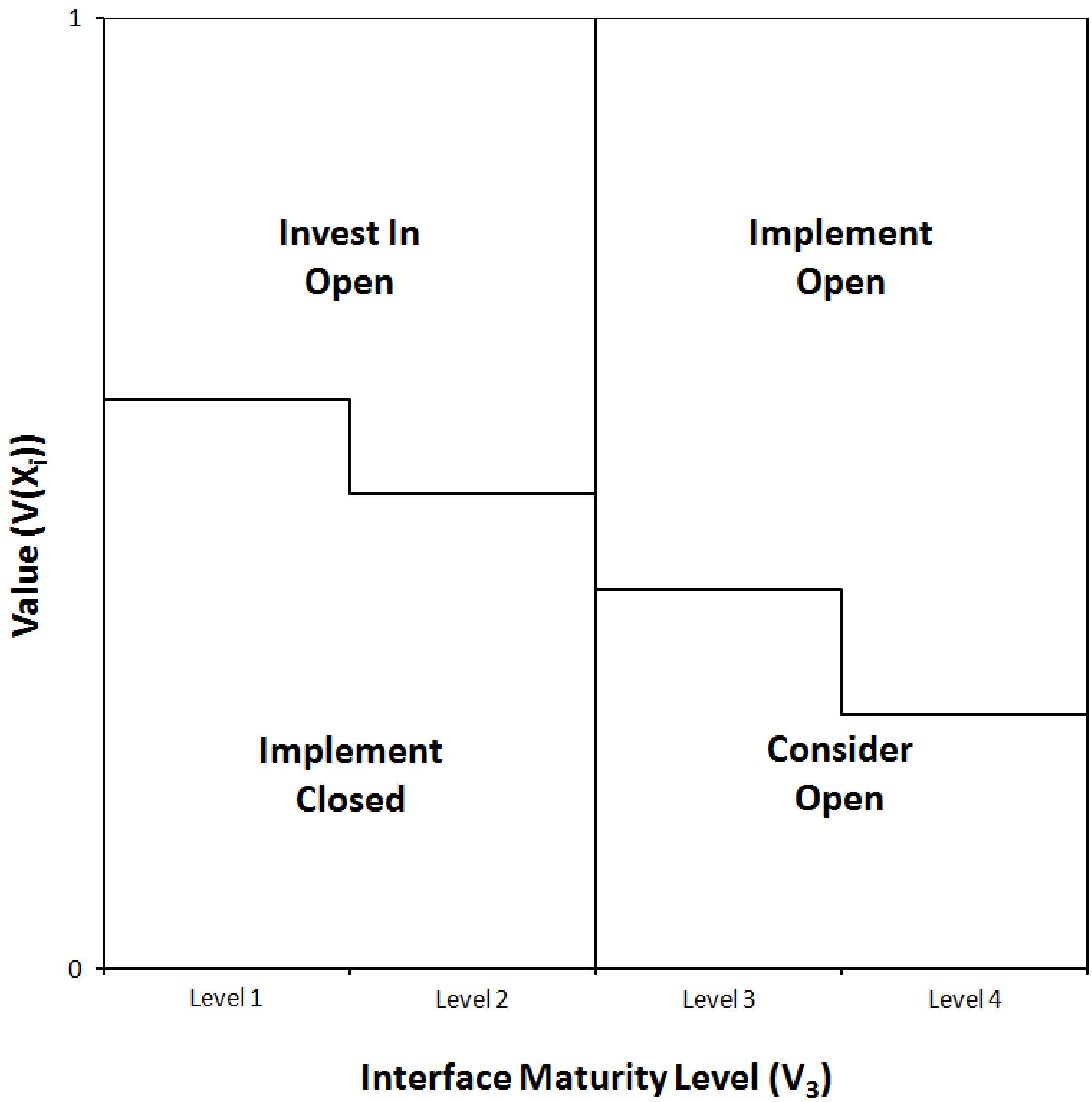


Figure 28: Alternative Threshold Value Score Interpretation

Treatment of uncertainty in the IEF

The IEF was developed under the assumption of certainty. While certain, or highly confident, answers can be provided for some of the value measures captured in the model, many of the measures include assessment of future events over the planning horizon. The assumption of certainty is not an issue for the evaluation of historical scenarios where there is no uncertainty in the data. This is not the case, when assessing present decisions. Including the treatment of uncertainty in the model is possible; however, the assessment difficulty, and subsequent value to decision making is unknown. In Chapter 2, a discussion of techniques for the development of multiattribute decision models, including uncertainty, was provided. There are three components necessary to support research in this area. First, an examination of the existing framework for uncertain elements. Second, one would need to determine if either of the techniques for implementing uncertainty in multiattribute decision models can be reasonably implemented while maintaining the usability of the tool for the general acquisition community. Finally, leveraging the information from the first two components one could elicit risk attitude data from members of the acquisition community.

Conclusions of Research

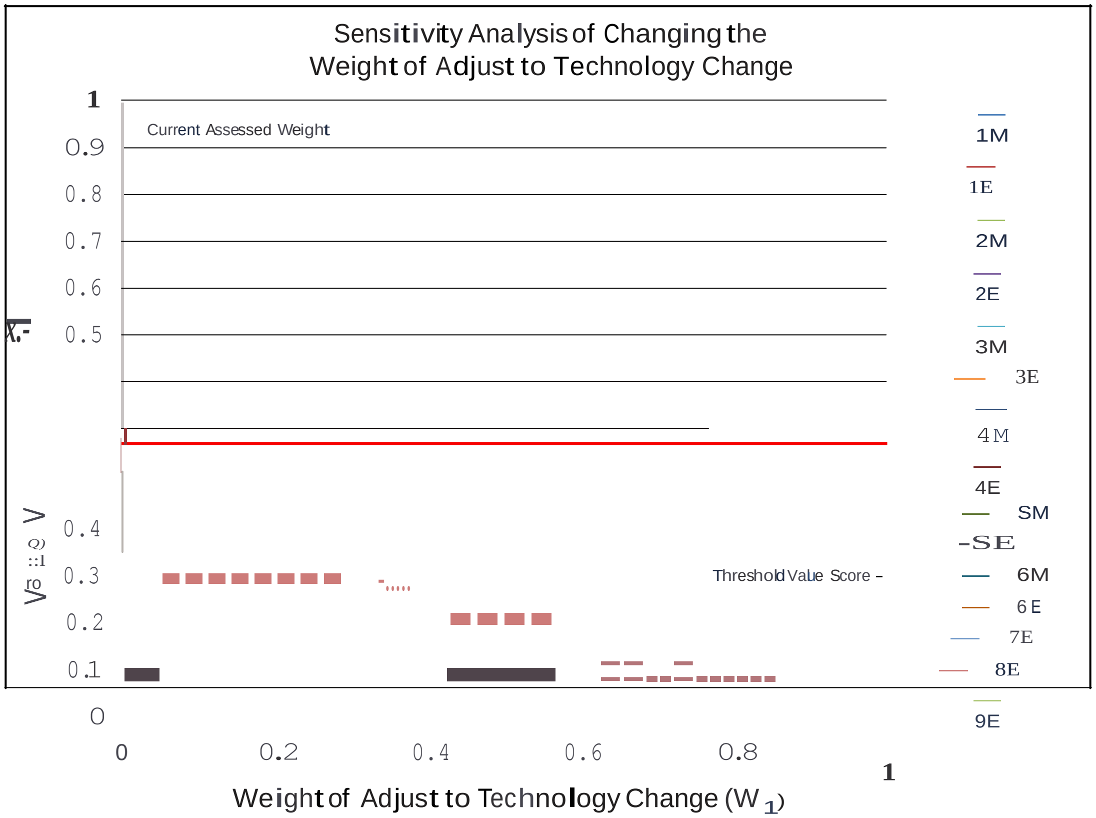
The IIM recommendations made by the IEF, with a threshold value score of 0.268, show positive correlation to the decision made by the program office on five of fifteen historical interface scenarios. This indicates that the IEF reflects the values of acquisition decision makers. The remaining ten scenarios indicated a misalignment between the model recommendations and the historic program office decisions. This indicates an area of further research to resolve the discrepancy.

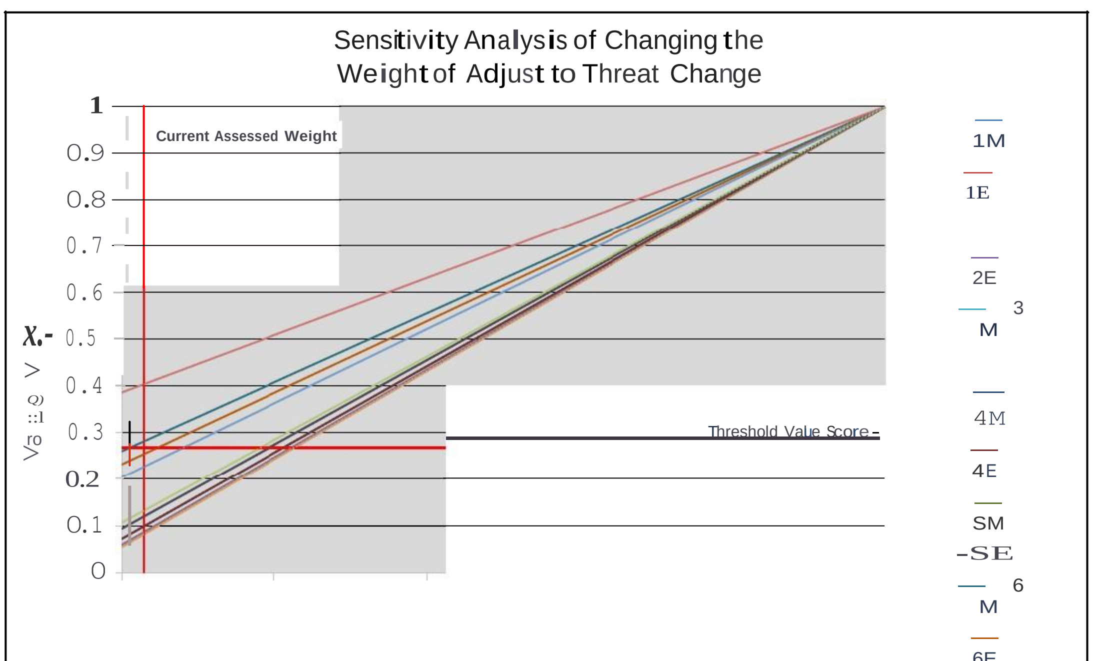
Adoption of the IEF could provide the acquisition community a repeatable, justifiable method for examination of open interfaces. Implementation of the IEF will rely upon additional data collection to support threshold value score refinement. Utilization of the IEF and analysis of recommendation accuracy will provide senior leaders the ability to objectively refine decision weights. Ultimately the IEF will provide the acquisition workforce a tool for OSA/MOSA decision making while simultaneously providing senior leadership a method to control, monitor, and refine the implementation of OSJTF guidance.

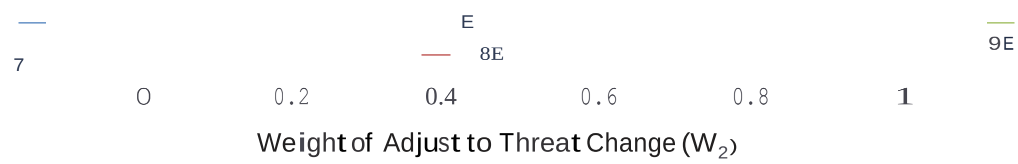
Appendix A: Scenario Scoring

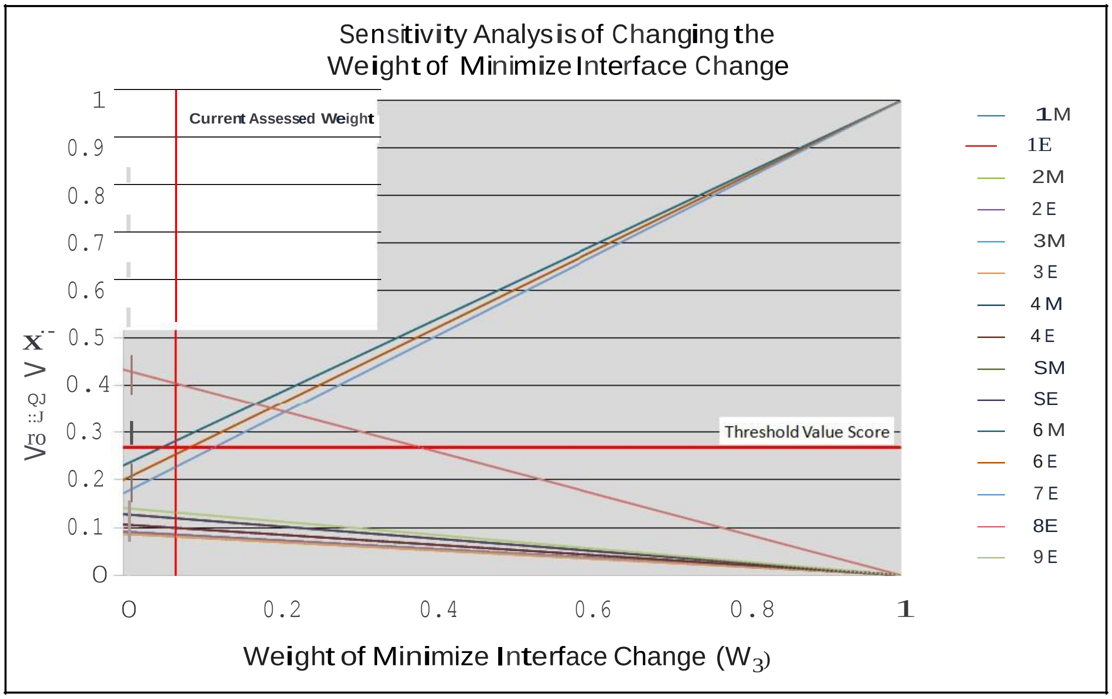
Alternative	1 M	1 E	2 M	2 E	3 M	3 E	4 M	4 E	5 M	5 E	6 M	6 E	7 E	8 E	9 E
# of Functionally Different Connected Systems	1	1	1	1	1	1	1	1	2	2	2	2	2	12	1
Average # of Functionally Equivalent Connected Systems	3	3	3	3	1	1	1	1	2	2	1	1	50	1	4
Average TRL of Connected Systems	8.3	8.3	9	9	9	9	9	9	8	8	9	9	9	8.4	9
Threat Environment	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Interface Maturity	1	1	1	1	1	1	1	1	1	1	4	4	4	1	1
Information Protection Level	3	3	3	3	3	3	2	2	2	2	2	2	1	5	2
User Community of Connected Systems	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
# of Integrations Over the Planning Horizon (10 yrs)	1	1	1	1	1	1	1	1	2	2	4	4	4	12	4
Cost Differential	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1
Schedule Urgency	2	2	2	2	2	2	2	2	2	2	4	4	1	5	2

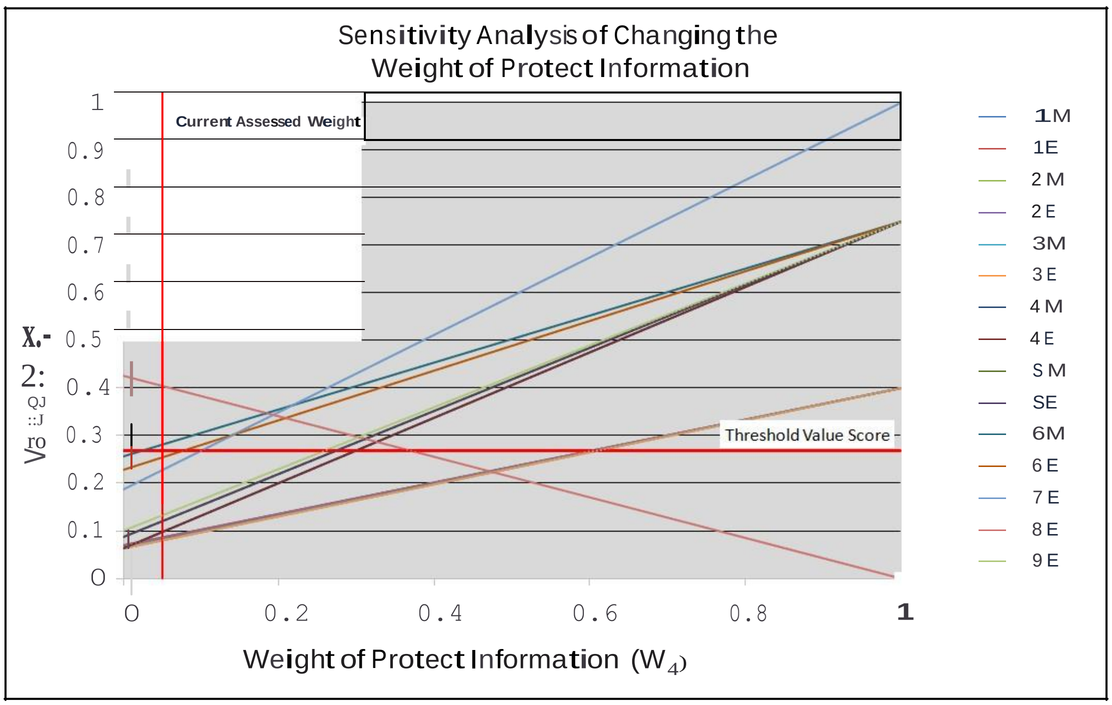
Appendix B: Sensitivity Graphs

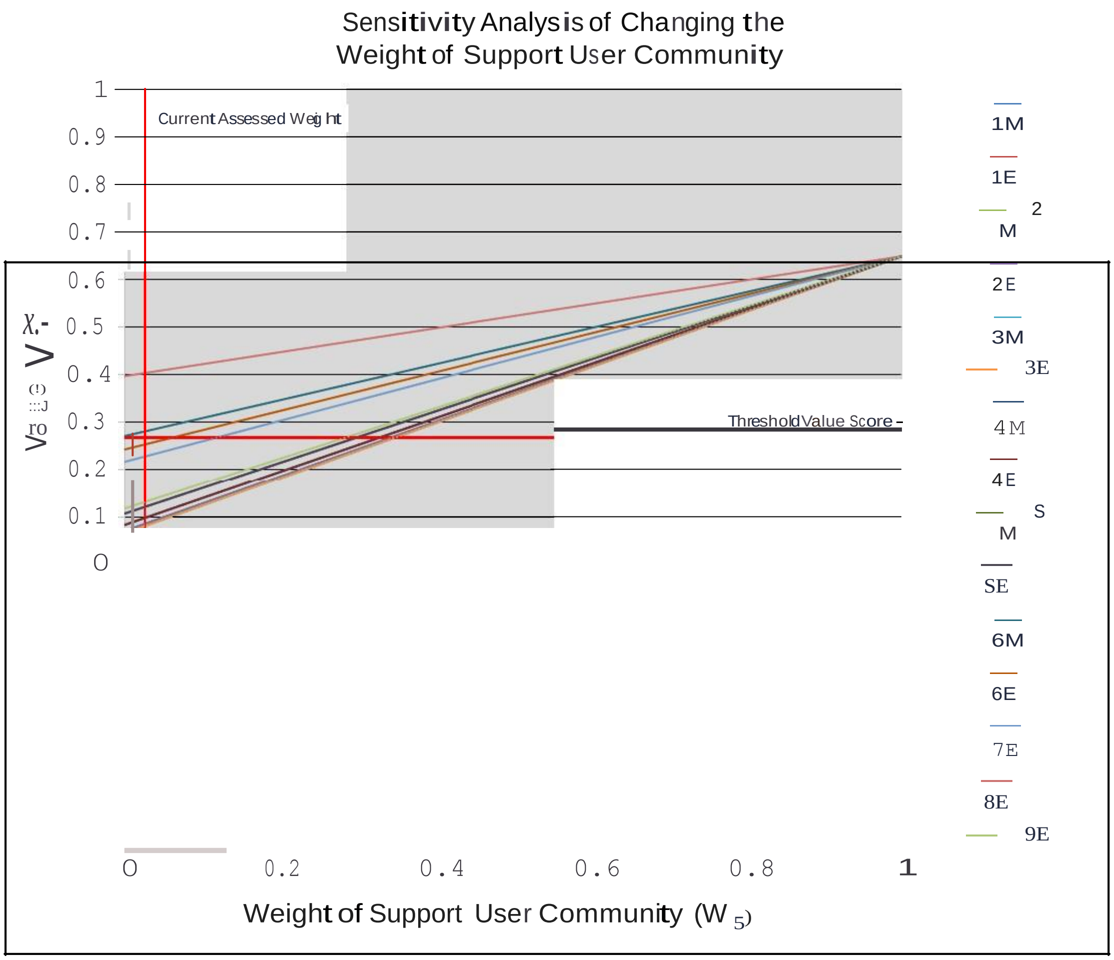




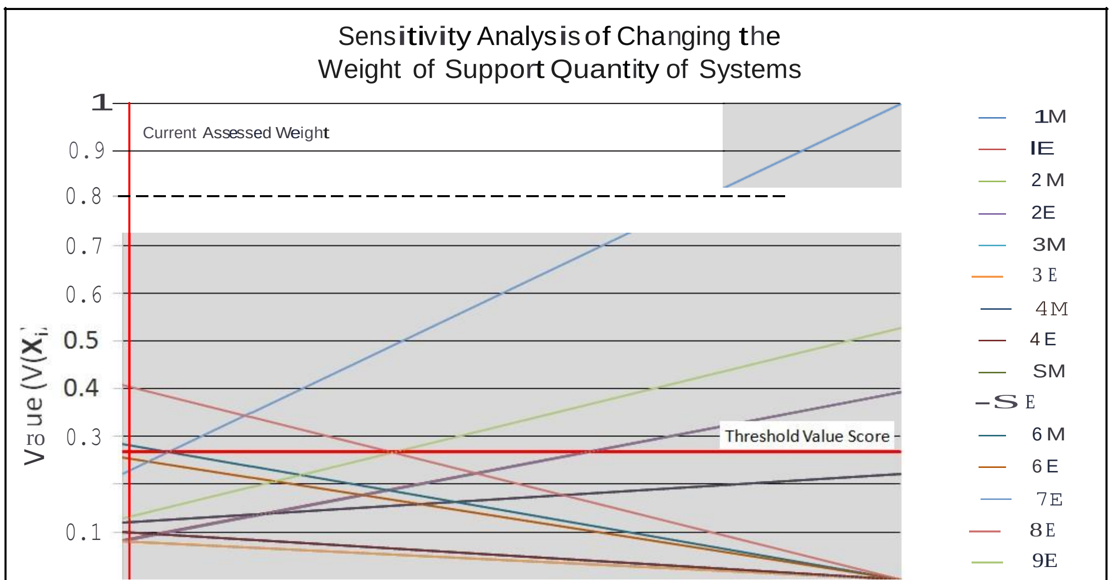

E
7
8E
9E
O
0.2
0.4
0.6
0.8
1
Weight of Adjust to Threat Change (W2)


Sensitivity Analysis of Changing the Weight of Minimize Interface Change
Current Assessed Weight
Threshold Value Score
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
Weight of Minimize Interface Change (W_3)
1M
1E
2M
2E
3M
3E
4M
4E
5M
5E
6M
6E
7E
8E
9E


Sensitivity Analysis of Changing the Weight of Protect Information
Current Assessed Weight
Threshold Value Score
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
Weight of Protect Information (W_4)
1M
1E
2M
2E
3M
3E
4M
4E
5M
5E
6M
6E
7E
8E
9E



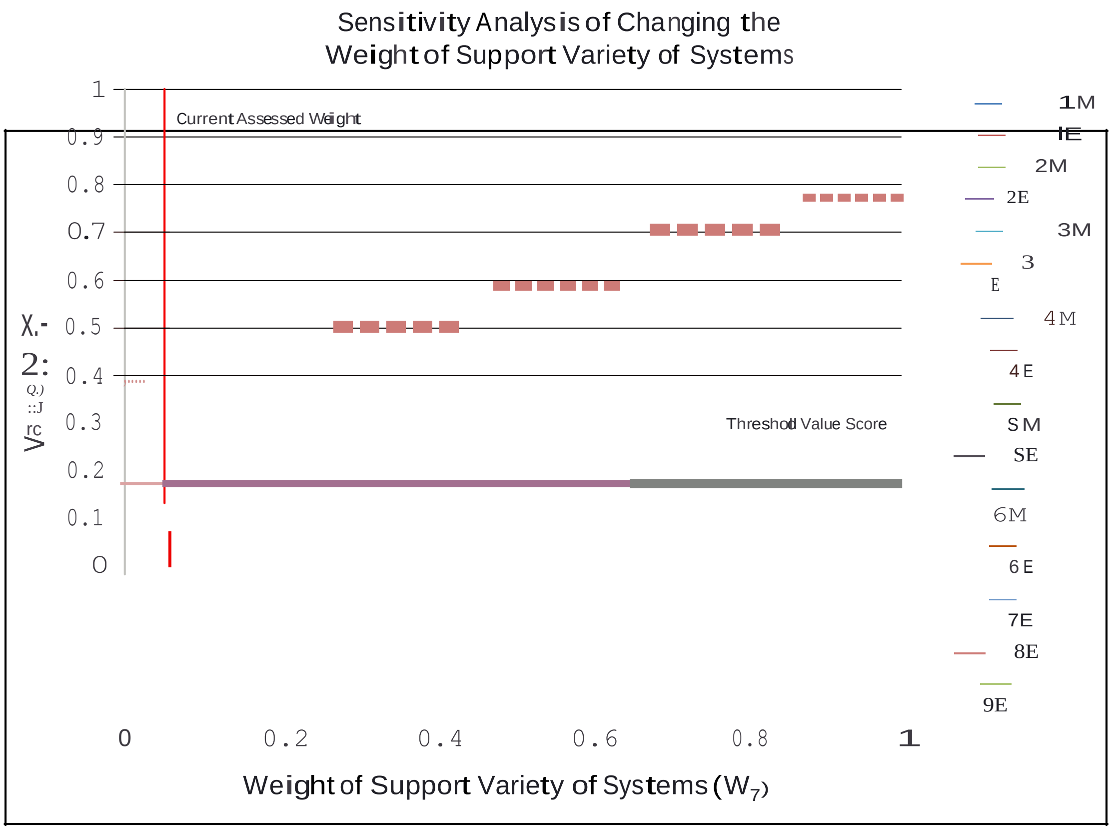
Sensitivity Analysis of Changing the
Weight of Support User Community
Current Assessed Weight
Threshold Value Score
Weight of Support User Community (W_5)
1M
1E
2M
2E
3M
3E
4M
4E
5M
5E
6M
6E
7E
8E
9E

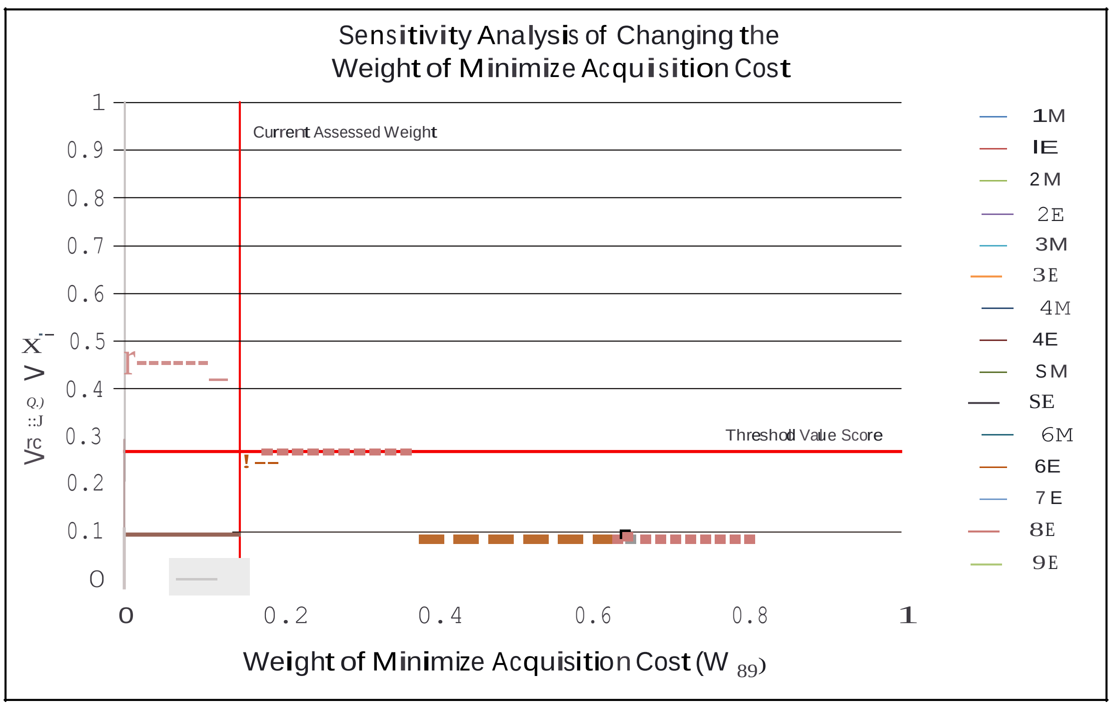


Sensitivity Analysis of Changing the
Weight of Support Quantity of Systems
Current Assessed Weight
Threshold Value Score
1M
1E
2M
2E
3M
3E
4M
4E
5M
5E
6M
6E
7E
8E
9E

0 0.2 0.4 0.6 0.8 1

Weight of Support Quantity of Systems (W_6)


Sensitivity Analysis of Changing the
Weight of Support Variety of Systems
Current Assessed Weight
Threshold Value Score
Weight of Support Variety of Systems (W7)
1M
IE
2M
2E
3M
3E
4M
4E
SM
SE
6M
6E
7E
8E
9E


Sensitivity Analysis of Changing the
Weight of Minimize Acquisition Cost
Current Assessed Weight
Threshold Value Score
Weight of Minimize Acquisition Cost (W89)
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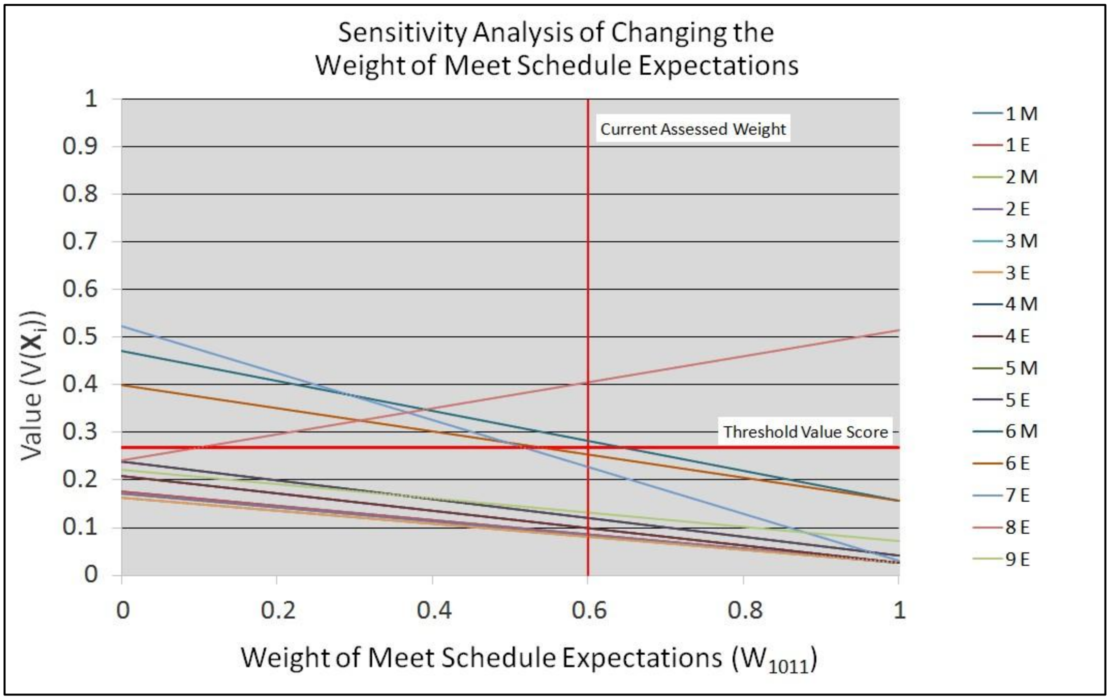
IE
2M
2E
3M
3E
4M
4E
SM
SE
6M
6E
7E
8E
9E


Sensitivity Analysis of Changing the
Weight of Meet Schedule Expectations
Current Assessed Weight
Threshold Value Score
Value (V(X_i))
Weight of Meet Schedule Expectations (W_{1011})
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
1 M
1 E
2 M
2 E
3 M
3 E
4 M
4 E
5 M
5 E
6 M
6 E
7 E
8 E
9 E

Bibliography

Air Force Acquisition - Organizations. (n.d.). Retrieved February 3, 2014, from http://ww3.safaq.hq.af.mil/organizations/index.asp

Assistant Secretary of Defense for Research and Engineering (ASD (R&E)). (2011, April). *Technology Readiness Assessment (TRA) Guidance.* Retrieved from http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf

Bard, J. F. (1992). A comparison of the the analytic hierarchy process with multiattribute utility theory: A case study. *IIE Transactions, 24*(5), 111-121.

Belton, V. (1986). A comparison of the analytic hierarchy process and a simple multi-attribute value function. *European Journal of Operational Research, 26*(1), 7-21.

Buede, D. M. (2000). *The engineering design of systems: models and methods.* John Wiley & Sons, Inc.

Clemen, R. T. (1996). *Making hard decisions: an introduction to decision analysis.* Belmont: Wadsworth Publishing.

Department of Defense Open Systems Architecture Data Rights Team. (2013). *DoD Open Systems Architecture: Contract Guidebook for Program Managers v1.1*. Washington, DC: Author. Retrieved from https://acc.dau.mil/adl/en-US/664093/file/73330/OSAGuidebook%20v%201_1%20final.pdf

Dillard, J. T., & Ford, D. N. (2007). Too little too soon? Modeling the risks of spiral development (No. NPS-AM-07-032). (pp. 484-501). NAVAL POSTGRADUATE SCHOOL MONTEREY CA GRADUATE SCHOOL OF BUSINESS AND PUBLIC POLICY.

F-16 Armament. (n.d.). Retrieved December 16, 2013, from F-16.net: http://www.f-16.net/f-16_armament.html

Federal Aviation Administration. (2013, March 19). *UAS FAQ*. Retrieved July 23, 2013, from Federal Aviation Administration Website: http://www.faa.gov/about/initiatives/uas/uas_faq/

Ford, D. N., & Dillard, J. T. (2008). Modeling the integration of open systems and evolutionary acquisition in DoD programs (No. NPS-AM-08-028). (pp. 83-104).

NAVAL POSTGRADUATE SCHOOL MONTEREY CA GRADUATE SCHOOL OF BUSINESS AND PUBLIC POLICY.

Ford, D. N., & Dillard, J. T. (2009). Modeling open architecture and evolutionary acquisition: implementation lessons from the ARCI program for the Rapid Capability Insertion process (No. NPS-AM-09-043). (pp. 207-236). NAVAL POSTGRADUATE SCHOOL MONTEREY CA GRADUATE SCHOOL OF BUSINESS AND PUBLIC POLICY.

Greenemeier, L. (2011, September 2). *Scientific American.* Retrieved July 23, 2013, from The Drone Wars: 9/11-Inspired Combat Leans Heavily on Robot Aircraft: http://www.scientificamerican.com/article.cfm?id=post-911-military-tech-drones

Hanratty, M. J., Lightsey, R. H., & Larson, A. G. (2002). *Open systems and the systems engineering process.* OFFICE OF THE UNDERSECRETARY OF DEFENSE (ACQUISITION AND TECHNOLOGY) WASHINGTON DC.

Howard, R. A., & Abbas, A. E. (2010). *GE 450 Course Packet Solutions* (Vol. 1). Illinois: Illini Union Bookstore.

Jurk, D. M. (2002). *Decision analysis with value focused thinking as a methodology to select force protection initiatives for evaluation (No. AFIT/GEE/ENV/02M-05).* AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING AND MANAGEMENT.

Keeney, R. L. (1992). *Value-focused thinking: A path to creative decision making.* Cambridge: Harvard University Press.

Keeney, R. L., & Raiffa, H. (1993). *Decisions with multiple objectives: preferences and value trade-offs.* Cambridge University Press.

Kirkwood, C. W. (1996). *Strategic decision making.* Wadsworth Publishing Co.

Lamartin, G. F. (2004, July 7). *Policy: Defense Acquisition Portal.* Retrieved from Defense Acquisition Portal: https://dap.dau.mil/policy/Documents/Policy/Dr%20Lamartin%20MOSA%20Memo%20(signed%207%20July%2004).pdf

Matheson, J. E., & Abbas, A. E. (2005). Utility transversality: a value-based approach. *Journal of Multi-Criteria Decision Analysis, 13*(5-6), 229-238.

Merrick, J. R., Parnell, G. S., Barnett, J., & Garcia, M. (2005). A multiple-objective decision analysis of stakeholder values to identify watershed improvement needs. *Decision Analysis*, *2*(1), 44-57.

Office of the Deputy Under Secretary of Defense for Acquisition and Technology, Systems and Software Engineering. (2008). *Systems Engineering Guide for Systems of Systems, Version 1.0.* Washington, DC: Author. Retrieved from http://www.acq.osd.mil/se/docs/SE-Guide-for-SoS.pdf

Office of the Undersecretary of Defense for Acquisition Technology & Logistics. (2007). *Department of Defense Directive 5000.01.* Washington, DC: Author. Retrieved from http://www.dtic.mil/whs/directives/corres/pdf/500001p.pdf

Office of the Undersecretary of Defense for Acquisition Technology & Logistics. (2008). *Department of Defense Instruction 5000.02.* Washington, DC: Author. Retrieved from http://www.acq.osd.mil/asda/docs/dod_instruction_operation_of_the_defense_acquisition_system.pdf

Office of the Undersecretary of Defense for Acquisition Technology & Logistics. (2013). *Interim Department of Defense Instruction 5000.02.* Washington, DC: Author. Retrieved from http://www.dtic.mil/whs/directives/corres/pdf/500002_interim.pdf

Open Systems Joint Task Force. (2004). *A Modular Open Systems Approach (MOSA) To Acquisition Version 2.0.* Author. Retrieved from http://www.acq.osd.mil/se/docs/PM-Guide-A-Modular-Open-Systems-Approach-to-Acquisition-2004.pdf

Parnell, G. S., Bresnick, T. A., Tani, S. N., & Johnson, E. R. (2013). *Handbook of decision analysis.* John Wiley & Sons, Inc.

Robbins, M. J. (2013, January). Class Example, SENG 643, Advanced Decision Analysis. Wright Patterson AFB, OH, USA: Air Force Institute of Technology.

Saaty, T. L. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation.* McGraw-Hill Inc.

Shoviak, M. J. (2001). School of Systems and Engineering Management, Air Force Institute of Technology (AU), AFIT/GEE/ENV/01M-20. AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING AND MANAGEMENT.

UAS Task Force Airspace Integration Integrated Product Team. (2011, March). *Unmanned Aircraft System Airspace Integration Plan Version 2.0.* Department of Defense. Retrieved from http://www.acq.osd.mil/sts/docs/DoD_2011_UAS_Airspace_Integration_Plan_(signed).pdf

Von Winterfeldt, D., & Edwards, W. (1986). *Decision analysis and behavioral research.* Cambridge University Press.

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14. ABSTRACT

This research develops a deterministic interface evaluation framework (IEF) in support of the principles identified in the Modular Open Systems Approach (MOSA). Interface evaluation in weapon system development requires a Decision Analysis (DA) method capable of handling a continuously growing alternative set and functioning with limited availability of senior decision makers. Value Focused Thinking (VFT) is selected as the best method for addressing the parameters of the framework. Inputs from the Medium Altitude Unamanned Aircraft System program office are used. An initial value threshold is established to guide open interface decisions, based on assessments of 15 historical decision scenarios. Open interface recommendations for the 15 scenarios are compared to previous program decisions, where the model supports past decisions for 5 of 15 scenarios. A sensitivity analysis is then conducted to examine the robustness of the framework to changing weights for cost, schedule, and performance, and the threshold for an open implementation decision. This evaluation framework provides a repeatable method for key interface evaluation that reflects the values of DoD acquisition leadership and the Open System Joint Task Force (OSJTF).

15. SUBJECT TERMS

Open System Architecture, Decision Analysis, Value Focused Thinking, Modular Open Systems Approach, Interface

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